THE UNIVERSITY OF ALBERTA

# ANALYSIS OF BED-LOAD TRANSPORT IN FLUMES USING NON-DIMENSIONAL REGIME THEORY PARAMETERS

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled

ANALYSIS OF BED-LOAD TRANSPORT IN FLUMES

USING NON-DIMENSIONAL REGIME THEORY PARAMETERS

submitted by A. Z. M. Fazlul Hoque in partial fulfilment of the requirements for the degree of Master of Science.

# ABSTRACT

Available world-data from flume experiments related to bed-load transport are analysed using non-dimensional Regime Theory parameters. The analysis is based on a functional relation derived from the full dynamical statement of a standard problem of bed-load transport in flumes. A relation between $V^2/(s-1)gd$ which is a special form of non-dimensional bed-factor taking care of buoyant specific gravity of bed-load, and the relative depth $d/{}^{m}_{w}D$ is proposed in the $d/{}^{m}_{w}D$ range of 10 to 100 and charge, C range of 0.0 to 10.0 parts per hundred thousand. The results obtained from the analysis of flume-data are checked with a limited amount of field data and reasonable consistency is found.

The influence of other relevant non-dimensional parameters in this range of $d/{}^{m}_{w}D$ and C are studied. The analysis confirms the speculation that there are definite phase differences in different ranges of d/D and different relations between relevant variables are to be used in these different phases.

An annotated table showing the ranges of values of relevant standardized parameters, mostly non-dimensional, for every set of experiments is provided. Annotation to this table is provided in a parallel table showing size distribution of materials used in each set of experiments. Brief descriptions of the shapes of these materials are given in various tables in the main body of the thesis.

# ACKNOWLEDGEMENTS

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# CHAPTER I

# INTRODUCTION

## 1.1 GENERAL

Channels - both natural and artificial- play an important role in the making and unmaking of human civilization. Therefore, man started, early, to manipulate and construct them to his advantage. But nature obeys its own laws. As a result, while many interferences with nature have been profitable, some have caused wastage of money and energy or even disaster, because of lack of understanding of the laws of nature.

Most of the channels that concern man, are alluvial, that is, they flow through the materials deposited by running water so that their boundaries are really self-formed. Usually they still carry the materials of which their boundaries are formed.

The science of these alluvial channels is comparatively new and a complete understanding of all the aspects of their behaviour is yet to be achieved. From the end of the last century, irrigation engineers in Indo-Pak subcontinent have tackled the problems of alluvial channels from the viewpoint of measured self-

adjustments of artificial channels that refused to retain their designed dimensions. Relations were developed for finally self-adjusted channels with marked success but they could not contain the measurable factors of sediment load till fairly recently, and then only roughly (Ref. 1).

In 1909, Gilbert (Ref. 2) took the problem to the laboratory and investigated, to the small scale available there but in terms of measurable bed-load, phases of transport outside of, and including those, observed in the field in the former Indian continent. His qualitative observations, published in 1914, added to knowledge but his measured relations were insufficient to produce an acceptable quantitative theory for so many different phases. Laboratory work has continued till today with widely contradictory quantitative results. FIGURES 1.1 to 1.4 from reference 3 compare predictions, based on several well-known bed-load formulas developed mainly from laboratory flume experiments, with the "observed" (measured) values in three (FIGURES 1.2, 1.3, and 1.4) different natural streams. "Observed" in FIGURE 1.1 means the results obtained from modified Einstein's formula by inserting measured values of slopes, velocities, depths and total bed-material load based on suspended load samples. It is evident from these figures that there is a wide scatter of results

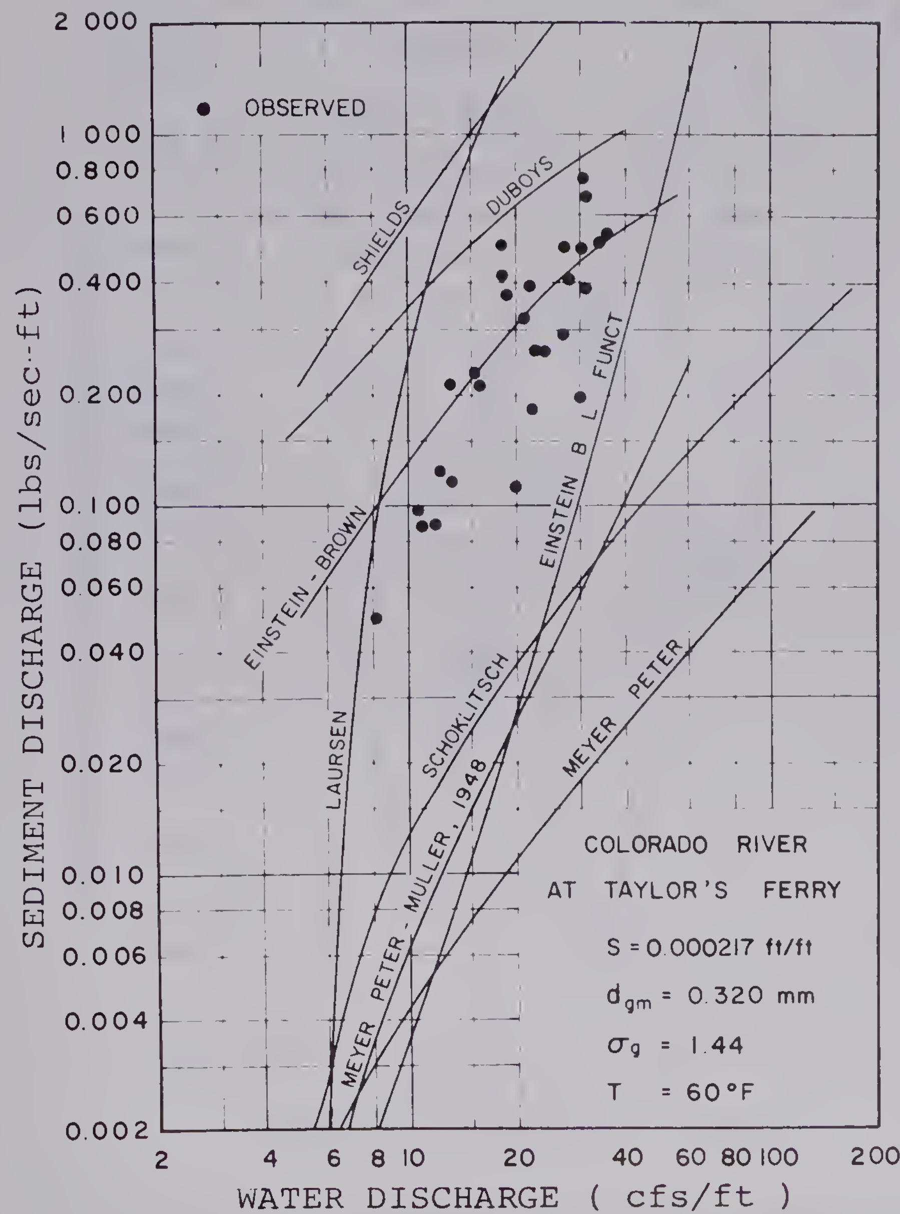



FIGURE 1-1 SEDIMENT RATING CURVES FOR COLORADO RIVER AT TAYLOR'S FERRY ACCORDING TO SEVERAL FORMULAS, COMPARED WITH MEASUREMENTS.

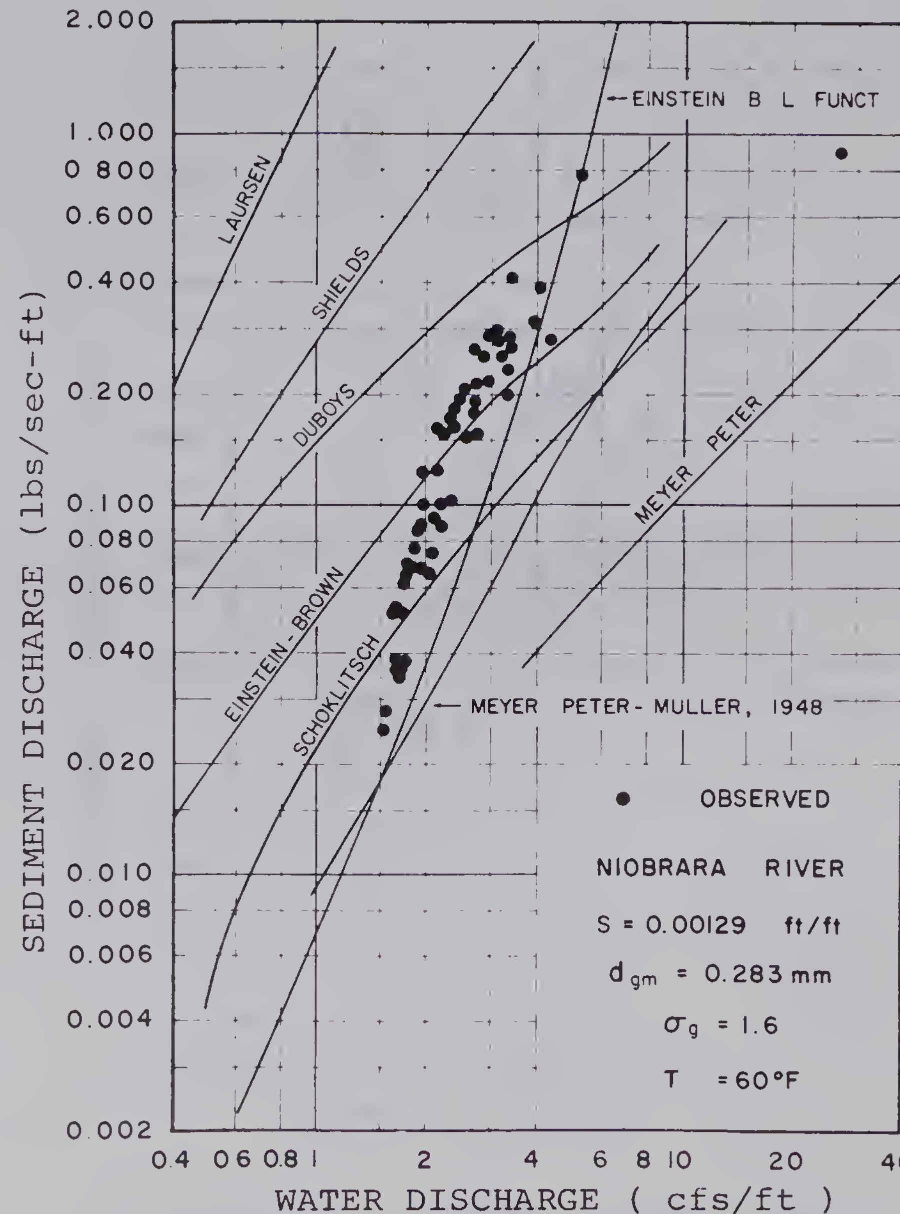



FIGURE 1-2 SEDIMENT RATING CURVES FOR NIOBRARY RIVER NEAR CODY, NEBRASKA ACCORDING TO SEVERAL FORMULAS, COMPARED WITH MEASUREMENTS.

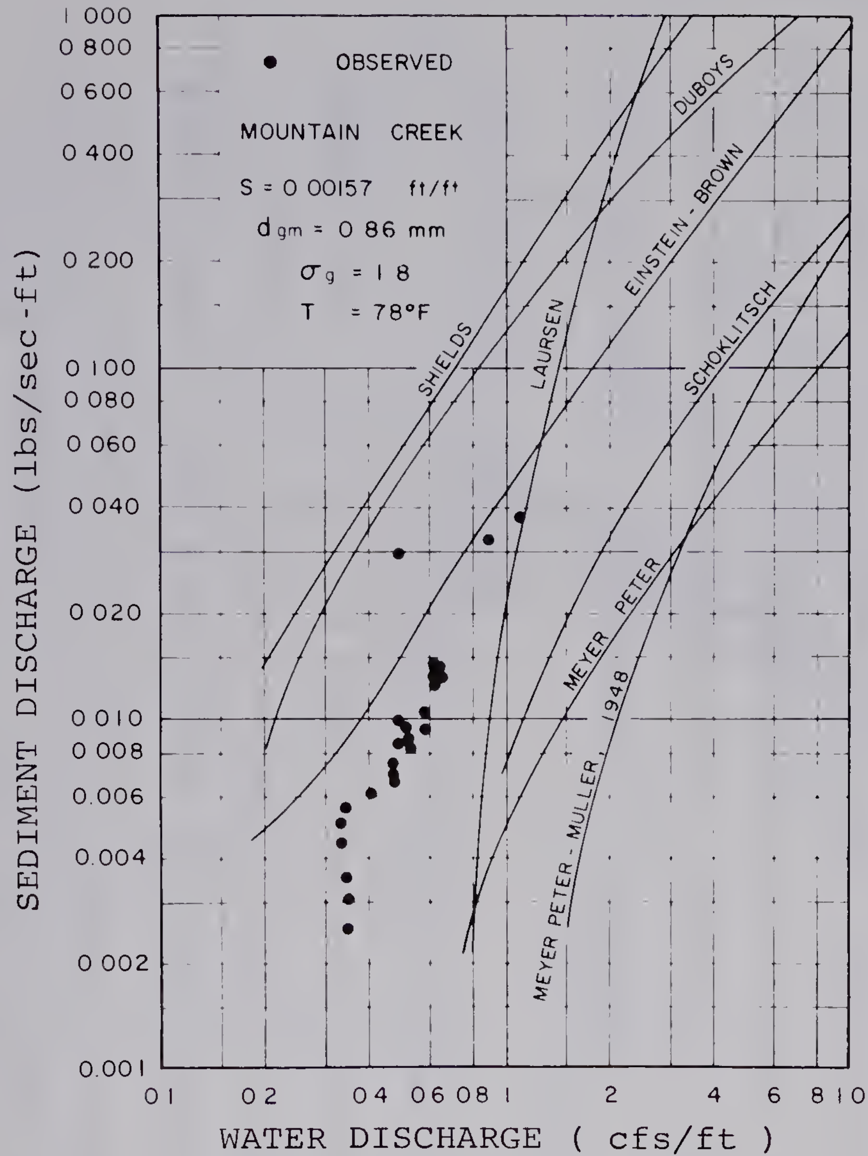



FIGURE 1-3 SEDIMENT RATING CURVES FOR MOUNTAIN CREEK NEAR GREENVILLE, SOUTH CAROLINA ACCORDING TO SEVERAL FORMULAS, COMPARED WITH MEASUREMENTS.

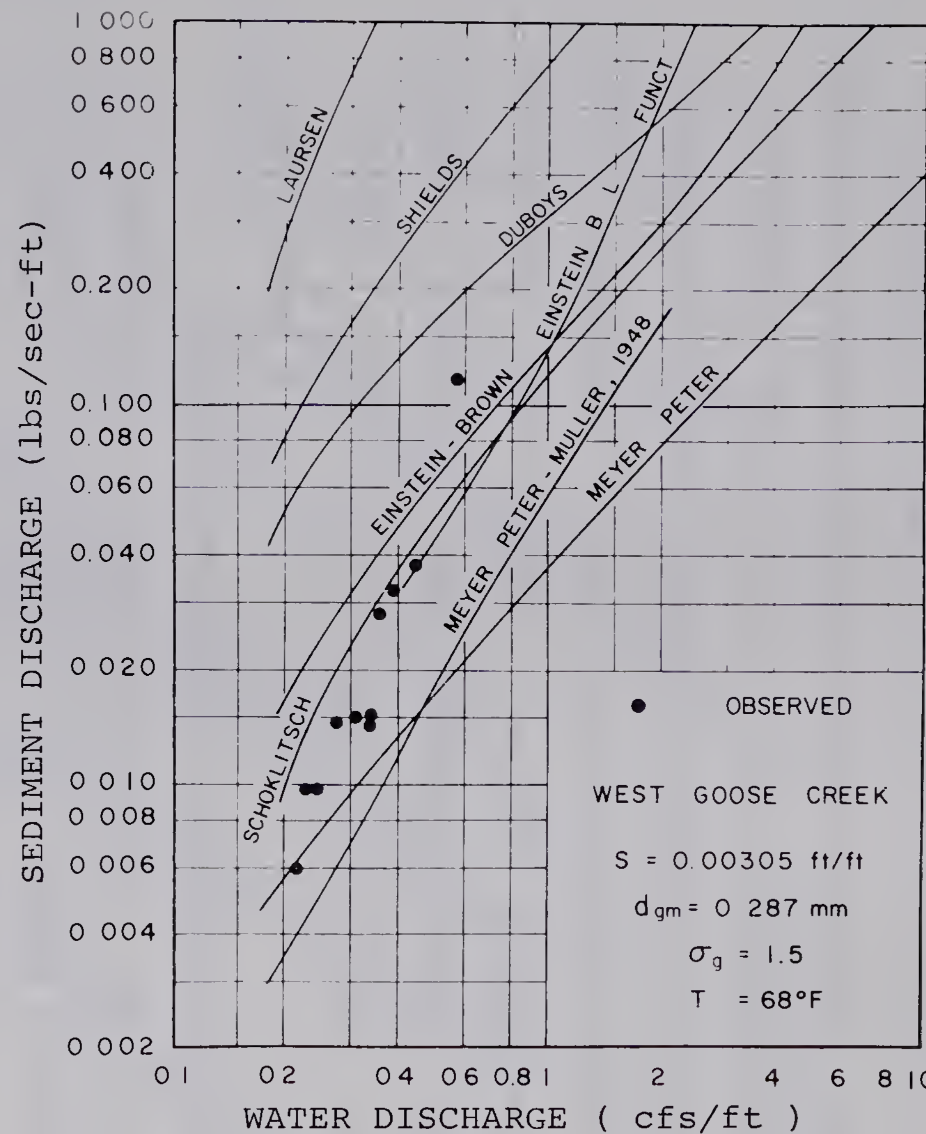



FIGURE 1-4 SEDIMENT RATING CURVES FOR WEST GOOSE CREEK NEAR OXFORD, MISSISSIPPI ACCORDING TO SEVERAL FORMULAS, COMPARED WITH MEASUREMENTS.

for different formulas and even the "observations" scatter as much as 50 to 100 percent from their mean. The authors (Ref. 3) admit that the statement - "In applying formulas, errors of 100 percent or more are to be expected" - by the Fontana Sedimentation Conference 1954 (Quoted from Ref. 3) applies to these cases. FIGURE 1.5 from reference 4 adds a regime type formula for bed-load transport in a flume, based on flume data.

Till recently, mobile boundary hydraulics has been limited to the specialists. However, UNESCO (NS/NR/17 of 15th October, 1962) (Ref. 1) has now listed "evolution of river-bed and sedimentation" as the third of nine major scientific problems of hydrology for the I.H.D. This new status, it is hoped, will result in more attention to the problems of both self-adjustment and transport of sediment.

## 1.2 AIM AND SCOPE OF STUDY

After analyzing the classic Gilbert data, Blench and Erb (Ref. 5) drew attention to the gaps in knowledge of sediment transport based on flume experiments. They also stated that d/D (depth of flow to grain size ratio) must be relevant at certain stages of flow and advocated the reanalysis of flume data to examine the relevance of d/D. The present work is in line with this thought and, here, an attempt will

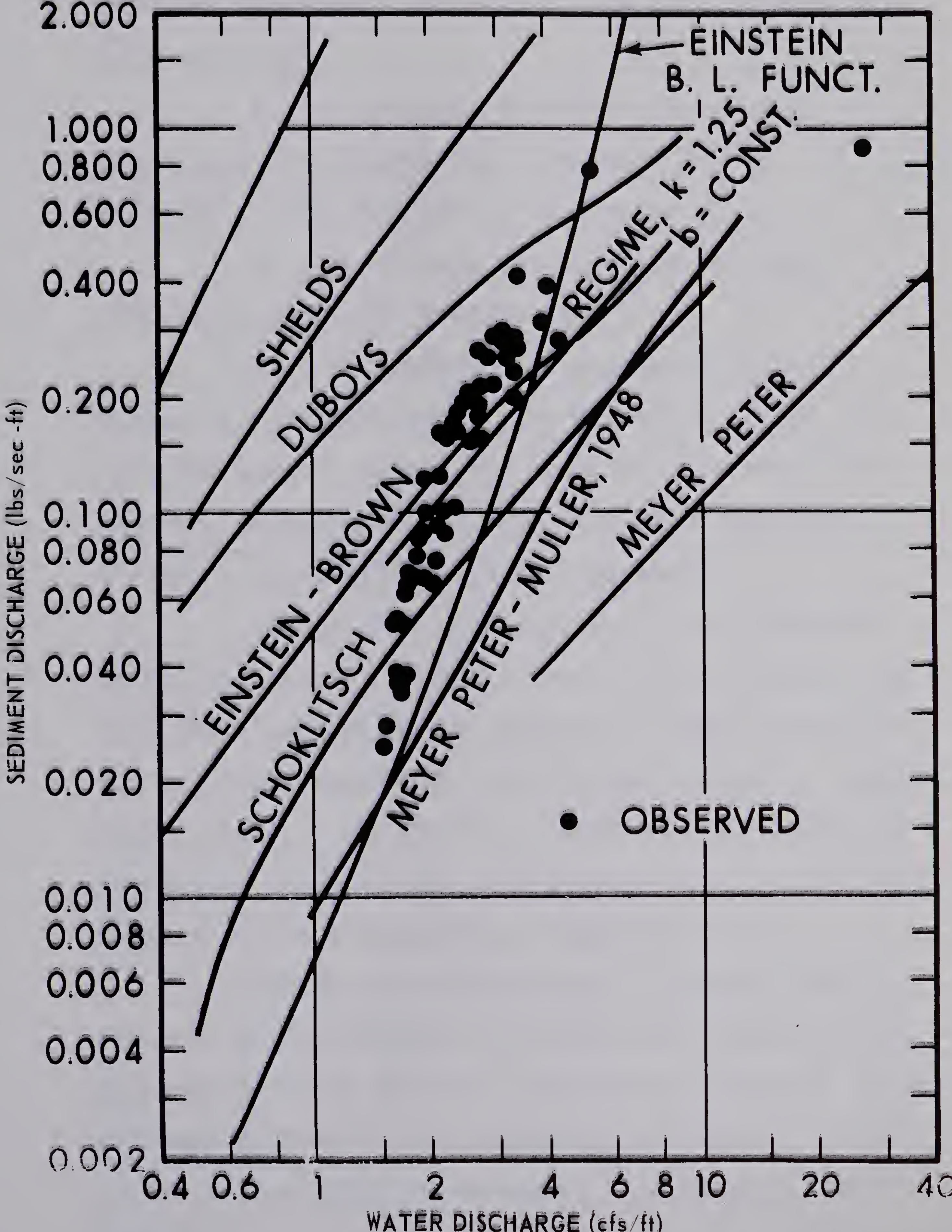



FIGURE 1-5 SEDIMENT RATING CURVES ACCORDING TO SEVERAL FORMULAS INCLUDING A REGIME THEORY-ONE BASED ON FLUME EXPERIMENTS. (REPRINTED FROM REF.1)

be made to find this aspect of river-bed evolution and bed-load transport. Therefore, the main objects of this study are:

1. - to analyze available world-data, nearly all from laboratory flume-experiments relevant to the transport of bed-materials.

2. - to attempt to reconcile the very conflicting formulas to-date and

3. - to consider the relevance of the result to river-behaviour, the aspects of which are on a far larger scale. The scope of this study is, however, confined to the condition where bed-load transport is considered to be very small.

Dimensional analysis, which has been neglected till fairly recently (Ref. 5,6,7) is used with a proper statement of the problem to ensure attention to the proper number of interrelated variables. Regime theory has been the guide in choosing non-dimensional parameters since it has proved successful in the field phase to which it purports to apply (Ref. 8).

The nature and validity of the data have required study, through the literature, and attention has been given to data on "initiation of motion" which although different from "cessation of motion" - which is the bottom limit of transport - is closely linked with it.

## 1.3 DEFINITIONS OF TERMS

Definitions of certain expressions and terms used in this study follow herein. Standard terms and their symbols with dimensions are given in article 1.4.

Sediment: - Any undissolved material that is transported by a flow under discussion. Normally, material, denser than water and carried by the flow of water is considered as sediment in River hydraulics.

Bed-load: - That part of the total sediment carried by the flow, which moves by saltating, sliding or rolling along the channel bed.

Sediment discharge: - The quantity, measured in units of mass, that passes a channel section per unit time on an average over a period of time.

Bed-material: - That part of the total sediment which remains in touch with the bed for most of the times, but may, at higher stages of flow, go into suspension.

Water-sediment complex:- The water together with the sediment.

Charge: - Ratio of dry weight of bed-load carried by the channel per unit time to the weight of water-flow per unit time, expressed in parts per hundred thousand.

Phase: - State of flow.

Size or Grade: - The size of a sediment particle is measured as the diameter of a sphere of the same material having the same terminal velocity of settlement in water.

Critical Tractive Force: - Tractive force ($\gamma dS$) at which the general movement of the bed starts.

General movement: - A condition of bed-load movement in which bed-particles up to and including the largest size are in motion.

Ripples: - Small triangular shaped bed-forms that appear on sand-bed at the beginning of motion of bed-load.

Bars: - Bars are deposits of bed-materials, in the channel section, that are too low to be classed as islands.

Dunes: - Bed-forms smaller than bars but larger than ripples. In longitudinal profile they are triangular having fairly gentle upstream slopes. They move downstream and are the principal sources of bed-roughness in sand-bed canals.

Antidunes: - Dunes that move upstream at supercritical flow.

Regime theory: - Inductive science of channel-evolutions based on observations of the dimensions of self-adjusted canal systems in the Indo-Gangetic plains (Ref. 1).

Silt-factor: - Lacey's silt-factor in his basic regime equation, related to silt size.

Bed-factor and Side-factor: - Lacey's silt-factor has been split by Blench into bed-factor and side-factor to account for different natures of non-cohesive bed

and relatively cohesive banks and are defined as $V^2/d$ and $V^3/b$ respectively.

Numeric: - A numeric is a dimensionless variable.

Incipient or Initiation condition: - Beginning of bed-load motion.

Zero bed-factor: - Bed-factor at small bed-load charge.

## 1.4 SYMBOLS USED IN THIS THESIS

The following symbols have been adopted, with mass, length and time as basic dimensions. Other symbols are described where they appear first.

| Symbol | Meaning | Dimensions |
|---|---|---|
| A | Cross-sectional area of flow | $L^2$ |
| a' | Long axis of an irregularly shaped stone | L |
| b | Breadth of the channel | L |
| b' | Intermediate axis of an irregularly shaped stone | L |
| C | Bed-load charge per $10^5$ | - |
| c' | short axis of an irregularly shaped stone | L |
| d | Depth of flow | L |
| D | representative size of bed-material | L |
| ${}^{m}_{w}D$ | Median size of bed-load by weight | L |
| $F_b$ | Bed-factor | $L/T^2$ |
| $F_{bo}$ | Bed-factor for small charge | $L/T^2$ |

| Symbol | Meaning | Dimensions |
|---|---|---|
| $f$ | Lacey's silt-factor | - |
| $G$ | Rate of sediment transport in lbs./ft. width | $M/LT$ |
| $g$ | Body force due to gravity | $L/T^2$ |
| $G_R$ | A representation of grain-size distribution which equals $\frac{1}{2}\left(\frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}}\right)$ | - |
| $G'$ | Submerged weight of bed-load transport per sec. per foot width | $M/LT$ |
| $K_s$ | Equivalent sand-grain roughness | $L$ |
| $K_b$ | Roughness coefficient of the type of Manning's n | - |
| $K'_b$ | Grain-roughness coefficient in Meyer-Peter's equation | - |
| $M$ | Kramer's uniformity modulus | - |
| $n$ | Manning's roughness coefficient | - |
| $Q$ | Fluid discharge-rate | $L^3/T$ |
| $q$ | Fluid-discharge rate per unit width of channel | $L^2/T$ |
| $R$ | Hydraulic radius | $L$ |
| $R_b$ | Bed-hydraulic radius equals A/bed width | $L$ |
| $S$ | Slope | - |
| $s$ | Specific gravity of bed-material | - |

| Symbol | Meaning | Dimensions |
|---|---|---|
| $t$ | Temperature | $\theta$ |
| $T$ | Time | $T$ |
| $V$ | Mean Velocity of flow | $L/T$ |
| $V_f$ | Fall velocity of bed-material. | $L/T$ |
| $V_*$ | Shear velocity | $L/T$ |
| $X$ | Non-dimensional factors relating to bed-load size distribution, shapes, texture etc. | - |
| $gS$ | Body force per unit mass resolved in the general direction of flow | $L/T^2$ |
| $\tau_o$ | Tractive force at the bed | $M/LT^2$ |
| $\tau_c$ | Critical value of $\tau_o$ beyond which general movement of bed-load occurs | $M/LT^2$ |
| $\pi$ | A constant = 3.14 | - |
| $\gamma, \gamma_w$ | Unit weight of fluid | $M/L^2T^2$ |
| $\gamma_s'$ | Submerged unit weight of solid | $M/L^2T^2$ |
| $\gamma_s$ | Unit weight of solid | $M/L^2T^2$ |
| $\rho, \rho_f$ | Mass density of fluid | $M/L^3$ |
| $\rho_s$ | Mass density of bed-material | $M/L^3$ |
| $\nu$ | Kinematic viscosity of fluid | $L^2/T$ |
| $\sigma_c$ | standard deviation in Charge, C | - |

## 1.5 ABBREVIATIONS

The following abbreviations are used in the body of this paper.

| | |
|---|---|
| UNESCO | United Nations Educational, Scientific and Cultural Organisation. |
| U.S. | United States |
| U.S.W.E.S. | United States Waterways Experiment Station |
| C.S.U. | Colorado State University |
| U.B.C. | University of British Columbia, Canada. |
| Ref. | Reference |
| Fig., Figs. | Figure, Figures respectively |
| ft. | Feet or Foot as the case may be |
| R.C.A. | Research Council of Alberta |
| N.R.C. | National Research Council of Canada |
| $F_{bo}$-Condition | Vanishingly small bed-load charge - Condition |
| Indo-Pak | India and Pakistan |
| I.H.D. | International Hydrologic Decade |
| Indo-Gangetic Plains | Plains deposited by the Indus and the Ganges. |
| Vs. | Versus |
| P.P.H.T. | Parts per hundred thousand |
| % | Percent |
| B.C. | British Columbia, Canada |
| Eq., Eqs. | Equation and Equations respectively |

| | |
|---|---|
| gm. | Grams |
| cm. | Centimeter |
| sec. | Second |
| / | per, such as ft./sec. |
| c.f.s., cusec. | cubic feet per second. |
| mm. | millimeter |
| fn. or fns. | function or functions |
| $\propto$ | varies with |

CHAPTER II

# LITERATURE REVIEW

## 2.1 GENERAL

Before discussing the method of analysis used in this study, it is necessary to discuss the sources of data and formulas. The present chapter outlines literature which is usually considered significant. As experimenters do not, normally, summarize the ranges of important variables in their data, and this failure may be relevant to the discrepancies among the results (FIGURE 1.1 to 1.5) the author starts by presenting these variables. FIGURES C-1 to C-38 (Appendix"C") show the frequency distribution of sizes of materials used by different experimenters whose data have been used in this analysis while table B-2 (Appendix"B") lists the ranges of various interrelated variables in each experimental set-up within the scope of this study. Table B-2 also shows the ranges of the values of various standardized groups, mostly non-dimensional, for research convenience (Ref. 4).

## 2.2 REVIEW OF LITERATURE RELATED TO MEASURED TRANSPORT

DuBoys (1879) (Ref. 9) was one of the first investigators in the field of sediment transport.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

He analysed the problem of transport by using the principle of conservation of energy and proposed the theory of "Tractive force". His idea of critical tractive force - which is the tractive force at which general movement of bed-materials takes place - is still shared by many investigators. DuBoys' tractive force equation, based on still earlier works of DuBuat (Ref. 10) is:

$$G = c_1 \tau_o (\tau_o - \tau_c) \qquad (2.2.1)$$

where

$G$ = rate of sediment transport in lbs./ft. width

$c_1$ = a coefficient but not a constant

$\tau_o$ = Tractive force or drag force at the bed in lbs./ft.$^2$

$\tau_c$ = Critical value of $\tau_o$

In 1935, Straub (Ref. 11) analysed the results of various investigators on the basis of Eq. 2.2.1 and presented the values of $c_1$ and $\tau_c$ for various sizes of sediment having specific gravity of 2.65. These figures are shown in table 2.1.

TABLE 2.1 Values of $c_1$ Calculated by Straub

| size of sediment in mm. | value of $c_1$ | value of $\tau_c$ in lbs./ft.$^2$ |
|---|---|---|
| 0.125 | 8.81 | 0.016 |
| 0.250 | 0.48 | 0.017 |
| 0.50 | 0.29 | 0.022 |
| 1.00 | 0.17 | 0.032 |
| 2.00 | 0.10 | 0.051 |
| 3.0 | 0.06 | 0.090 |

The next and most comprehensive work in this field was that of G. K. Gilbert (Ref. 2) who investigated the problem in terms of measurable bed-load, described the various phases of transport and studied the individual effects of charge, flume-width, discharge and sediment size on equilibrium depth and slope. Gilbert disagreed with the commonly known law of sixth power (quantity of sediment transported varies with the sixth power of flow velocity) and mentioned the work of Deacon (1894) who believed that the quantity transported varies with the fifth power of velocity. Gilbert explained that the sixth power law pertains to the maximum size of the grain that a given current is competent to move. This has been supported by William W. Rubey (Ref. 12).

Engels, H. and Kramer, H. (1932) (Ref. 13) presented a rather different form of critical tractive force equation in terms of the physical characteristics of the sand particles in a mixture - which when converted to English units reduces to:

$$\tau_c = 0.00138 \frac{D}{M} (\gamma_1 - \gamma) \qquad (2.2.2)$$

where

M = Uniformity modulus describing grain size distribution

D = Mean grain size in inches

$\gamma_1$ = Unit weight of sand in lbs./ft.$^3$

$\gamma$ = Unit weight of water in lbs./ft.$^3$

$\tau_c$ = Critical Tractive force in lbs./ft.$^2$

Kramer was one of the pioneers to introduce size distribution of the sediment as a variable in the problem. He described the distribution of the sediment by what he called "uniformity modulus".

MacDougall (1933) (Ref. 14) shared the opinion about the effect of grain size distribution and pointed out the quite different behaviour of uniform and graded sands though their mean grain size may be the same. He agreed to the fact of different phases of bed-movement but concluded from his flume experiments that the amount of sands moved is independent of the phases of movement and that the bed-load is strictly a function of tractive force. He proposed the following empirical relation for bed-load transport

$$G = a_1 S^{b_1} (Sq - Sq_c) \tag{2.2.3}$$

where $G$ = bed-load in lbs./ft. width/sec.

$S$ = slope, $q_c$ = unit water discharge at critical condition

$q$ = water discharge in cusec./ft. width.

$a_1$, $b_1$ are constants depending upon the specific gravity and mechanical composition of the sand.

Analysing mostly Gilbert data supplemented by some of his own, Schoklitsch (1934) put forward the following relation for uniform quartz grains.

$$G = \frac{86.7}{D^{\frac{1}{2}}} S^{1.5} (Q - bq_c) \tag{2.2.4}$$

[illegible]

[illegible]

$$[illegible]$$

[illegible]

$$[illegible]$$

[illegible]

$$[illegible]$$

where $G$ = rate of bed-load movement

$D$ = grain size in inches

$S$ = slope

$Q$ = water discharge in c.f.s.

$b$ = breadth in ft.

$q_c$ = critical discharge per unit width of flume in c.f.s.

From 1932 to 1935 the U.S.W.E.S. performed a series of experiments to determine the force of flowing water required to move materials composing the bed of the Lower Mississippi River (Ref. 10). The analysis of data was based on the DuBoys' principle of tractive force and the following empirical transport equation was developed.

$$G = \frac{1}{n}\left(\frac{dS - doSo}{K_1}\right)^m \qquad (2.2.5)$$

where $G$ = rate of movement in lbs./ft. width/hour (dry weight)

$n$ = Manning's roughness coefficient

$dS$ = product of depth in feet and slope

$doSo$ = product of depth in ft. and slope at which the linear plot of G against "dS" meets the "dS" axis.

$m$, $K_1$ are the dimensional constants obtained from a logarithmic plot of the data. One of the most widely quoted criteria for the initiation of motion of

non-cohesive grains on flat bed is the Shields' diagram (FIGURE 2.2.1). Shields (1936) showed that the tractive force could be expressed as a function of the dimensionless parameter $V_*.D/\nu$ where D is the diameter of the sediment grain. In his experiments Shields used uniformized materials ranging from approximately 0.1 to 5 mm. in size and approximately 1.06 to 4.25 in dry specific gravity. He concluded that non-dimensional tractive force $\tau_o / \gamma_s' D$ - now called mobility number is independent of $V_*.D/\nu$- now called grain size Reynolds' number when the latter exceeds approximately 500 and for incipient motion, with gravels exceeding approximately 3 mm. in grain-size, the expression $\tau_o / \gamma_s' D$ has a constant value ranging from 0.04 to 0.06. However, his text shows that he appreciated the possibility of complexities associated with bed-forms. These figures (0.04-0.06,500) have been disputed by Komura (1963) and Zeller (1963) and Neill (1966) (Ref. 15). Shields, apart from his well-known incipient-condition relationship, also suggested a bed-load formula (Ref. 16)

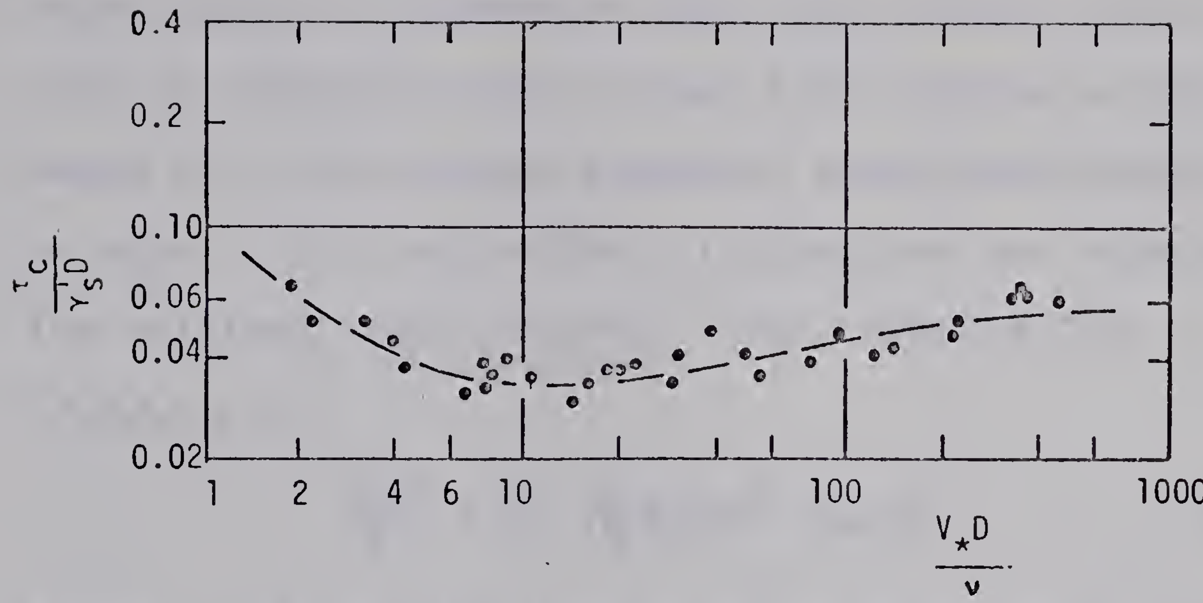
$$\frac{Gs}{qS} = 10 \left(\frac{\tau_o - \tau_c}{\gamma(s-1)D}\right) \qquad (2.2.6)$$

where q = discharge intensity

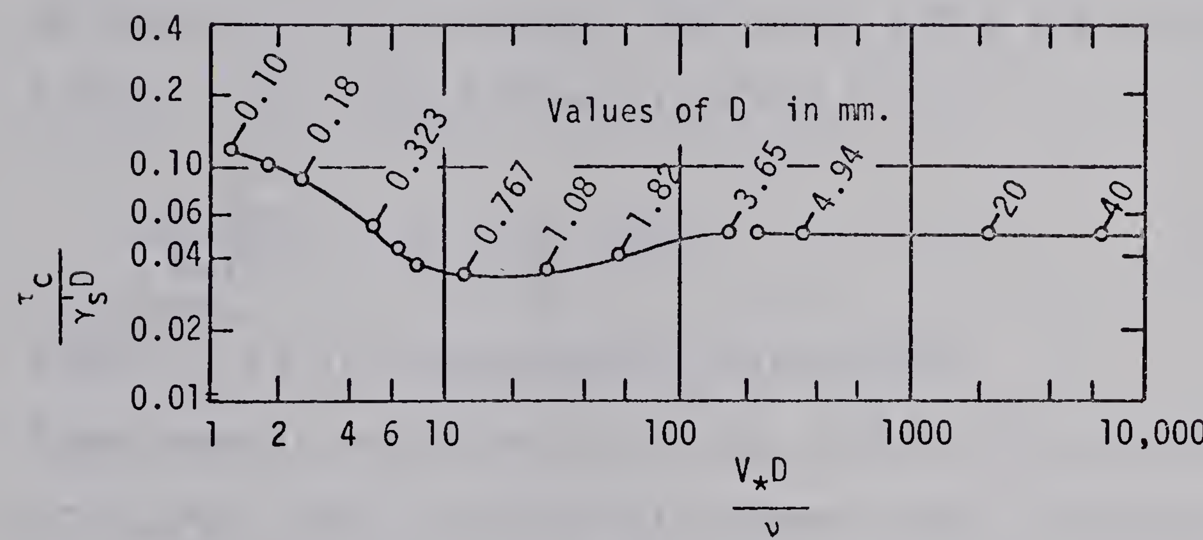
S = bed-slope

s = specific gravity of the sediment

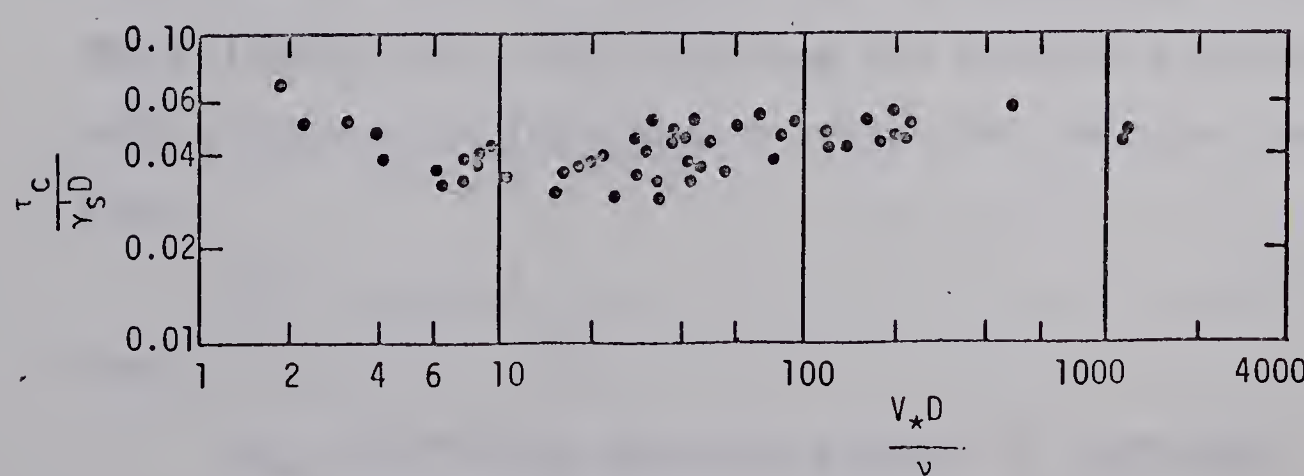
and other terms are as defined before. Again his text shows he was aware of possible qualifications.




Shields diagram showing original data points and curve as usually quoted.

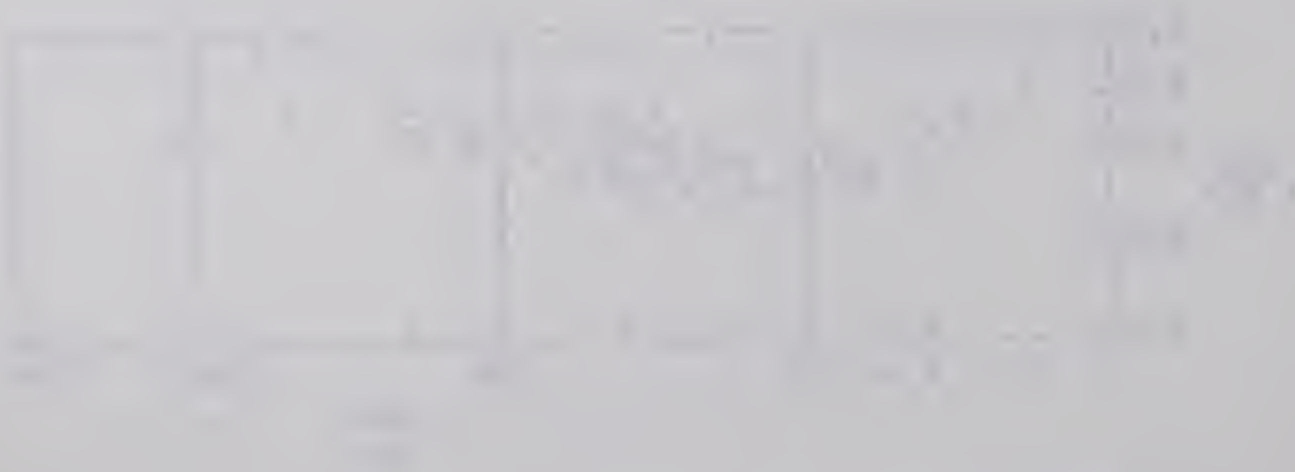



Shields-type curve by Iwagaki, with grain-size values for standard-density material as added by Komura.




Shields-type diagram by Zeller, with supplementary data by Meyer-Peter and others.

FIGURE 2-2-1 SHIELDS' DIAGRAM ON "INITATION OF MOTION" AND SHIELDS' TYPE DIAGRAM BY IWAGAKI AND ZELLER. (REF. 15)



Vanoni (Ref. 9) commented that this formula applies only to sediments which do not form ripples or high waves i.e. for sediments greater than approximately 2 mm. in size. C. M. White (Ref. 17) derived two relations for critical tractive force. For inviscid flow - ($V_*D/\nu > 3.5$)

$$\frac{\tau_c D^2}{p} = \frac{\pi}{6} (\gamma_s - \gamma_w) D^3 \tan\varphi \qquad (2.2.7)$$

where p is a packing factor and is equal to $D^2$ times the number of grains per unit area and $\varphi$ is the angle of repose of the material and other terms are as defined before. For viscid flow ($V_*D/\nu < 3.5$)

$$\frac{\tau_c}{(\gamma_s - \gamma_w) D} = c_1\, p\, \frac{\pi}{6} \tan\varphi \qquad (2.2.8)$$

where $c_1$ is an experimental coefficient.

Experimental verification of Eq. 2.2.8 for a 50 fold range of $V_*D/\nu$ (from 0.04 to 2.1) showed that the value of "$c_1 p$" and hence the value of $\tau_c/(\gamma_s - \gamma_w)D$ is independent of $V_*D/\nu$ which thus contradicts the results of Shields in this zone. Chang (1939) (Ref. 18) following and extending MacDougall's work proposed the following relation for critical tractive force

$$\tau_c = c_1 . s_e . D \qquad (2.2.9)$$

where

$s_e$ = effective specific gravity of submerged sand particles

$c_1$ = a constant

D = mean diameter of sand particle in mm.

$\tau_c$ = critical unit tractive force in lb./ft.$^2$

Using Eq. 2.2.9 Chang proposed a transport formula of DuBoys' type for uniform sand.

$$G = \frac{Kn}{\tau_c^2} \left( \tau_o - \tau_c \right) \tag{2.2.10}$$

where K is a constant and all other terms are as defined before. He pointed out that the advance of ripples, which he assumed to be the same as the velocity of sand movement, is proportional to the fifth power of the mean velocity of the flow and that irrespective of the modes of transport sorting takes place in graded sands. One widely used bed-load formula - that of Meyer-Peter and Muller (1948) is:

$$0.25 \rho^{1/3} G'^{2/3} = \tau_o \left[ \frac{q_b}{q} \left( \frac{K_b}{K'_b} \right)^{3/2} \right] - 0.047 \, \gamma'_s D \tag{2.2.11}$$

where the term in the square bracket is a correction factor which allows for wall effects and bed-form roughness. In Equation 2.2.11,

G' = submerged weight of bed-load transported per sec. per foot width.

$\rho$ = mass density of fluid.

$\tau_o$ = $\gamma dS$. where $\gamma$, d are unit weight and depth of water respectively and S is the channel slope.

$\gamma'_s = (\gamma_s - \gamma_w)$ = submerged unit weight of sediment

D = size of the bed-materials

$q$ = unit fluid discharge, $q_b = V_{mean} \times R_b$

$R_b$ = bed hydraulic radius = A/bed width

$V_{mean} = K_b R_b^{2/3} S^{\frac{1}{2}}$

$K'_b$ = Grain roughness coefficient = $32/K_s^{1/6}$, $K_s$ in feet.

Equation 2.2.11 is dimensionally homogeneous. One remarkable exception to this conventional approach of tractive force theory to the sediment transport problem is that of H. A. Einstein (1942) (Ref. 19). Einstein argued that it was difficult to distinguish, exactly, a condition when bed-materials start moving and he refused to use the term critical tractive force for the flow condition when transportation begins. He viewed the transport problem as a random process and assumed that the number of bed-load particles moving out of a bed-area of unit width and length per second is a function of the probability that the lifting force of the flow exceeds the submerged weight of the particle. He observed that the bed-material moves in steps or jumps and assumed that the average length of the step of an individual particle is some function of its diameter. Based on these assumptions and physical reasoning he developed a relation, using dimensional analysis, of the form

$$\frac{G}{V_f D} = \text{fn}\left(\frac{1}{\Psi}\right) \qquad (2.2.12)$$

where $G$ = rate of sediment transport/ft. width

$V_f$ = particle fall velocity

$D$ = diameter of grain

and $\frac{1}{\Psi} = fn\left(\frac{\tau_o}{\gamma(s-1)D}\right)$

Putting $\phi = G/V_f D$ , Eq. 2.2.12 takes the form

$$\phi = fn\left(\frac{1}{\Psi}\right) \qquad (2.2.12a)$$

Einstein, then plotted the experimental data using Eq. 2.2.12a. His plot is shown in FIGURE 2.2.2. Henderson (1966) (Ref. 16) plotted the $\phi - \frac{1}{\Psi}$ relation in a form due to Brown (Ref. 20) who proposed the equation

$$\phi = 40 \left(\frac{1}{\Psi}\right)^3 \qquad (2.2.13)$$

for the upper straight line portion of the curve shown in FIGURE 2.2.3. Brown pointed out that for low values of $\phi$ and hence of G, the curve swings away from the straight line to the asymtote $\frac{1}{\Psi}$ = 0.056 which corresponds to Sheilds' initiation criterion. Kalinske (Ref. 21) derived a relationship very similar to that of Einstein but he used shear velocity, $V_*$ in place of particle fall velocity used by Einstein. Kalinske's plot of $G/V_*.D$ against $1/\Psi$ is shown in FIGURE 2.2.4. The constant value of $\tau_o/\gamma_s'.D$ for initiation of motion, obtained from Kalinske's plot is almost twice that obtained from both Shields' and Einstein's plots. E. M. Laursen (1958) (Ref. 22.) presented the following relation for total sediment transport

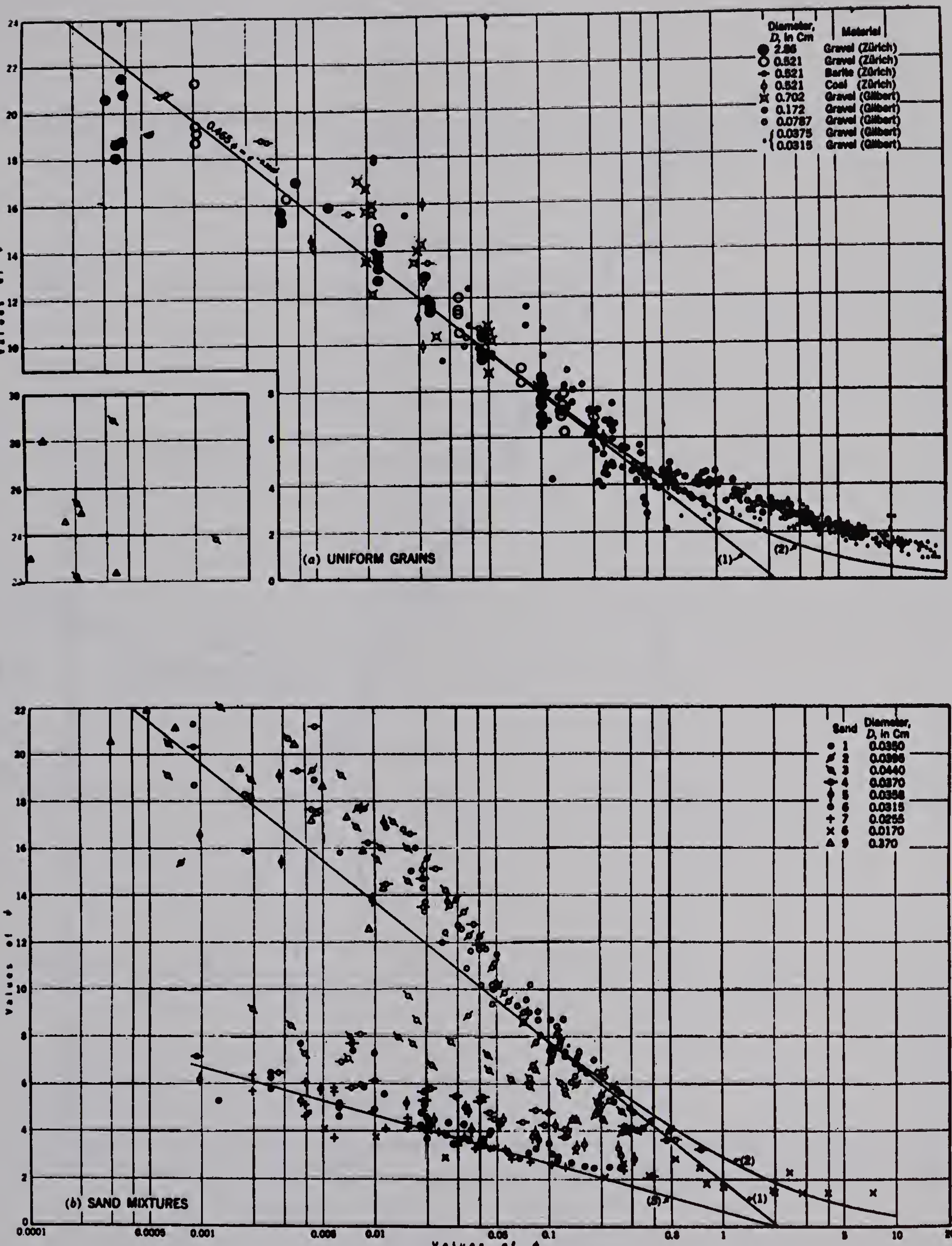



FIGURE 2-2-2(a) & (b) EINSTEIN'S BED-LOAD FUNCTION.
GRAPHS OF $\Phi$-$\Psi$ RELATION. (REPRINTED FROM REFERENCE 9).

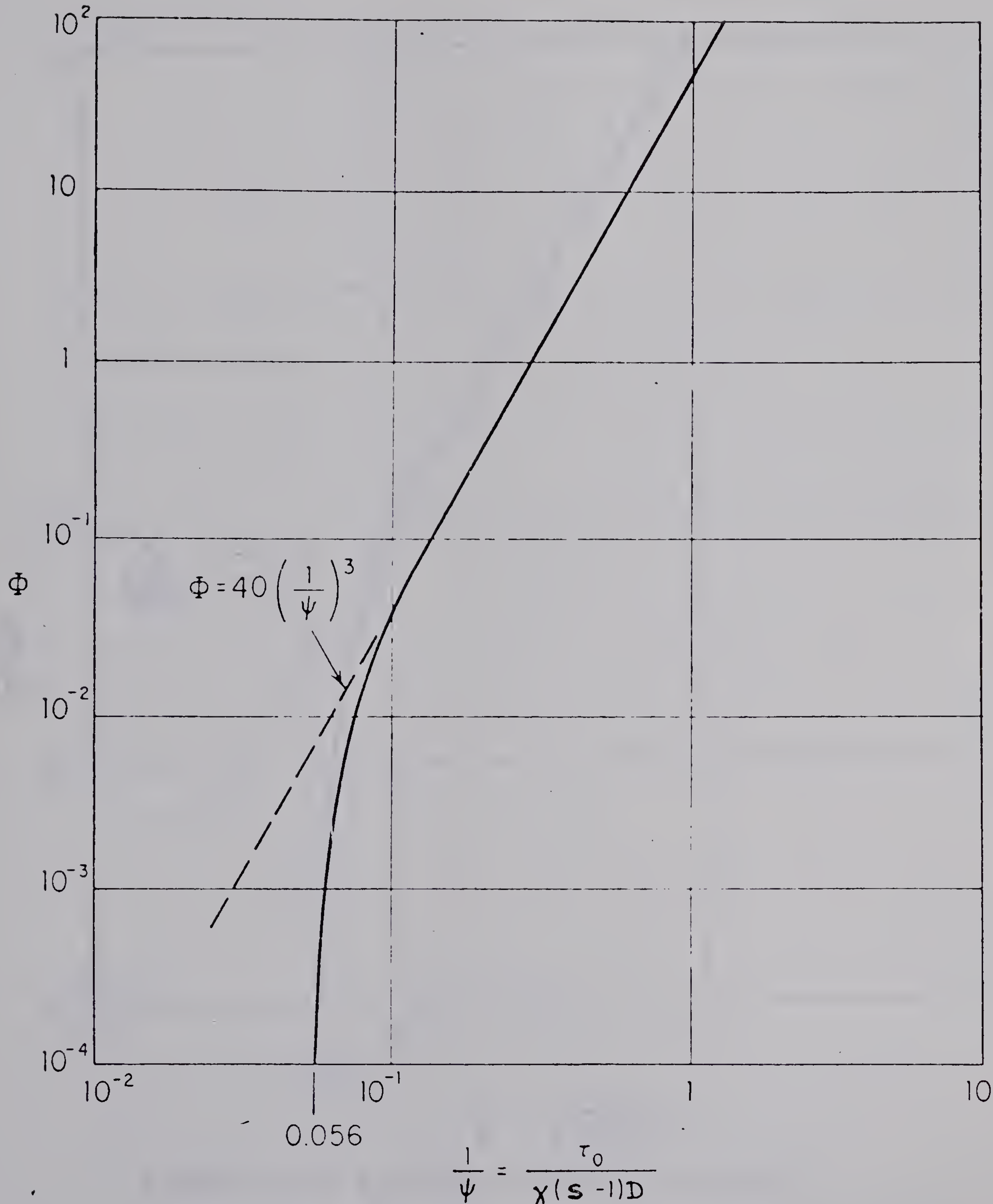



FIGURE 2-2-3 HENDERSON'S PLOT OF EINSTEIN'S BED-LOAD FUNCTION (REPRINTED FROM REFERENCE 16)

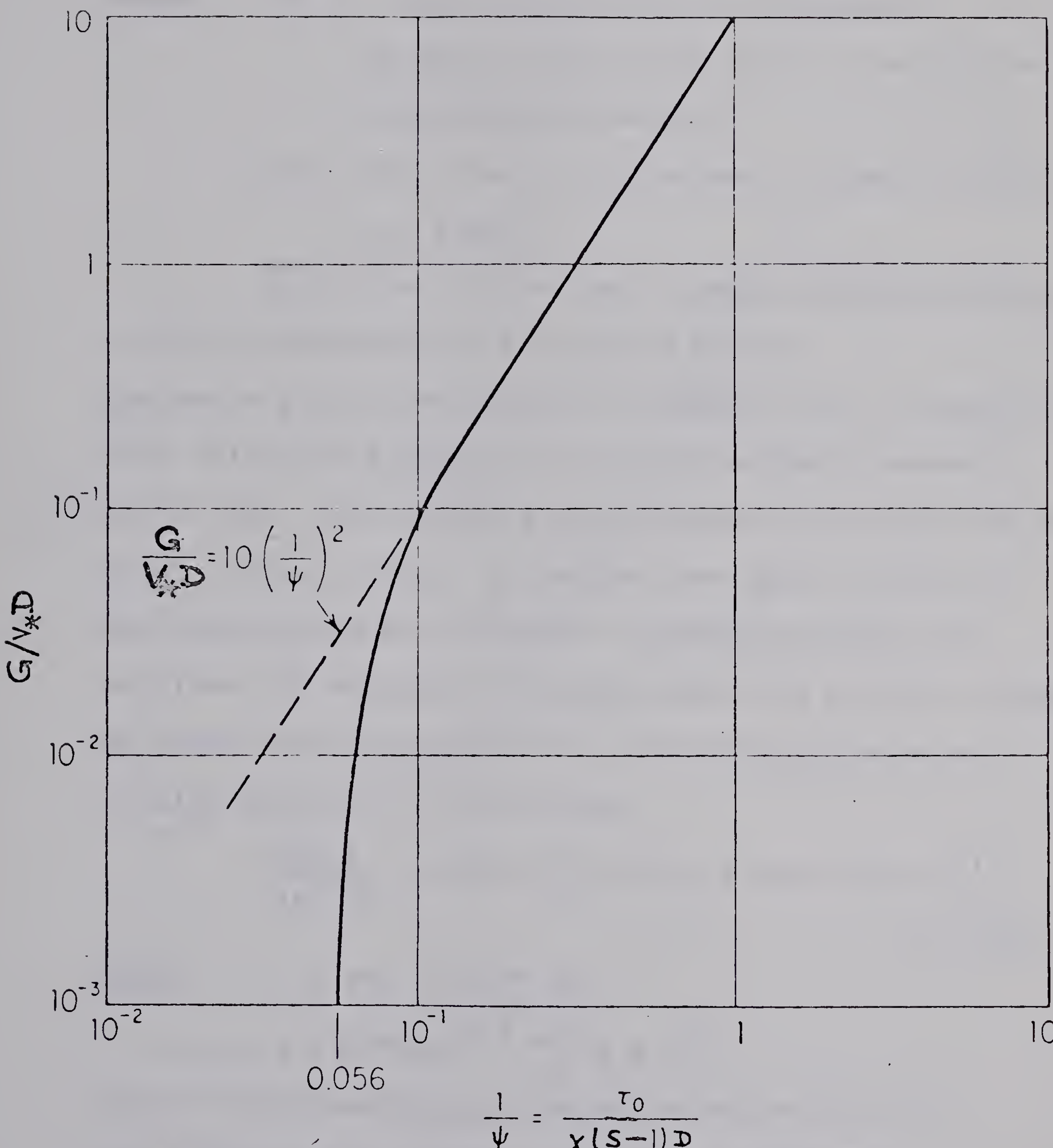



FIGURE 2-2-4 KALINSKE'S PLOT OF BED-LOAD FUNCTION(REPRINTED FROM REF.16)

$$\frac{\bar{C}}{\Sigma P(\frac{D}{d})^{7/6}(\frac{\tau_o'}{\tau_c} - 1)} = fn\left(\frac{V_*}{V_f}\right) \qquad (2.2.14)$$

where $\bar{C}$ = mean concentration of suspended or bed or total load as the case may be in percent by weight

$\Sigma p$ = sum of the contributions of each fraction p of size D.

$\tau_o'$ = shear stress due to grain resistance alone

- other parameters are as defined before.

Laursen's plot is reproduced in FIGURE 2.2.5. Assuming that saltation accounts for all the sediment movement Yalin (Ref. 23) deduced a semi-empirical relation for the total sediment load. He assumed the uplift force on the particle to be a function of shear velocity, $V_*$ and from the relation of uplift force and particle weight, he worked out the path of the saltating particle and finally arrived at the relation

$$\frac{G(s-1)}{V_*.D.s} = 0.635\, r\left[1 - (\log_e\,(1+a.r.))/a.r\right] \qquad (2.2.15)$$

where $r = (\tau_o - \tau_c)/\tau_c$ and

$a = 2.45.s^{-0.4}(\tau_c/\,\gamma.s.D)^{\frac{1}{2}}$

Yalin's expression fits some experimental data for the particle size range of 0.7 mm. to 28.6 mm. Henderson (Ref. 16) described some of Yalin's assumptions as unrealistic since the latter assumed that the uplift force is not dependent on time and the increase

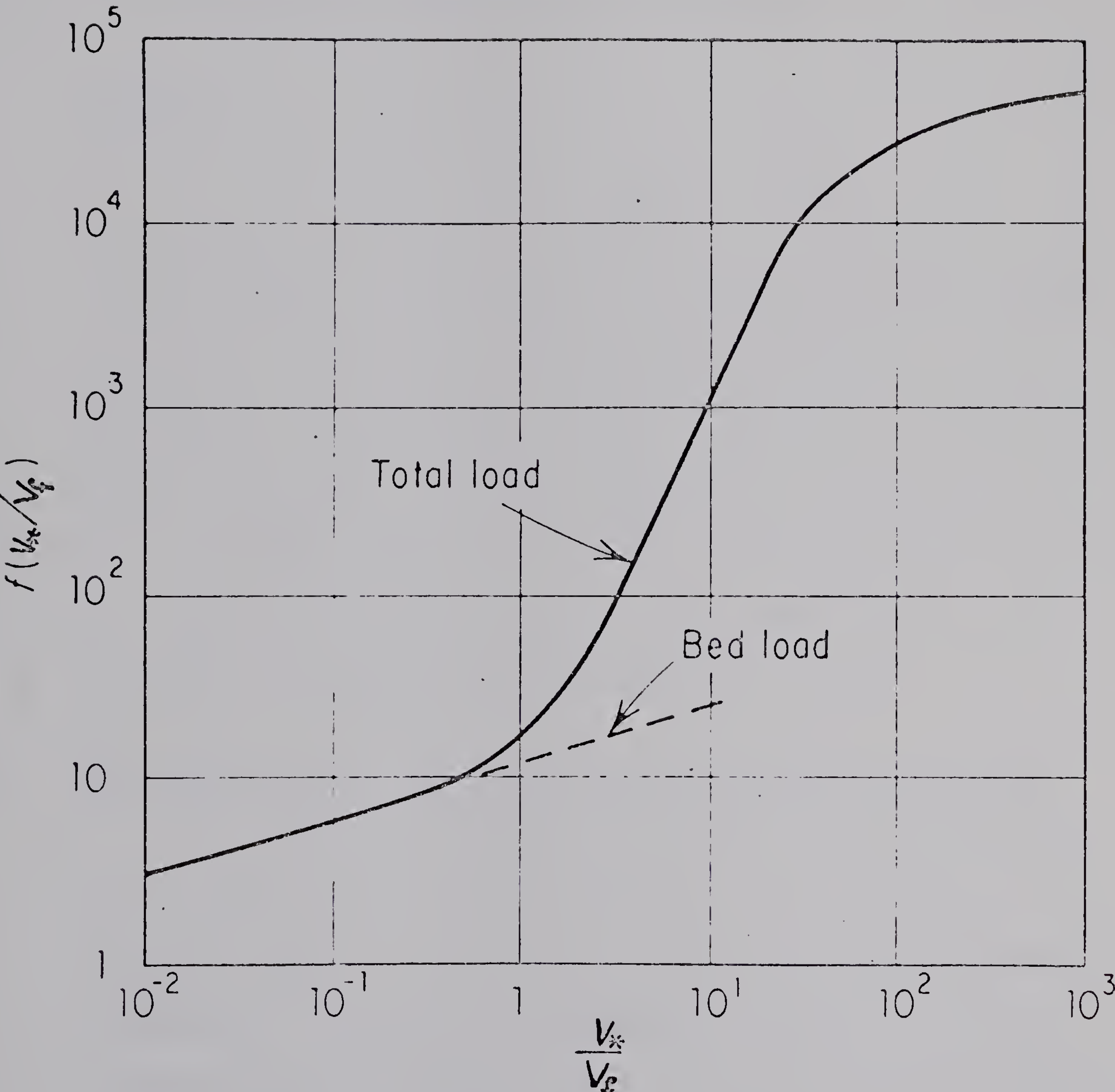



FIGURE 2-2-5 SEDIMENT-LOAD FUNCTION AFTER E.M. LAURSEN(REPRINTED FROM REF.16)

in sediment discharge is attributed to the increase in the range of saltation path rather than to the increase in the number of grains in motion.

# CHAPTER III

# THEORETICAL BACKGROUND OF ANALYSIS

## 3.1 GENERAL

In this chapter a brief history of the development and the outline of the regime theory will be presented as the method of analysis of this study is based on the principles of this theory. A brief outline of dimensional analysis will also be presented here. Finally, brief description of the data used in this analysis will be provided. Detailed descriptions of these data, especially of most experimental set-ups will be found in reference 28.

## 3.2 REGIME THEORY - HISTORY OF DEVELOPMENT AND OUTLINE

The term "regime" has been defined by Prof. Blench (Ref. 1) as "the behaviour of a channel, over a period, based on conditions of water and sediment discharge, breadth, depth, slope, meander form and progress, bar movement, etc. ----" and regime theory studies the self-adjustment of these channels to long-term steady regime. Regime theory originated mainly from the field experiences gained in construction, maintenance and extension of the world's largest canal systems in the Indo-Pak sub-continent since

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

the latter part of the nineteenth century. The canal systems in the Indo-Gangetic plains have three degrees of freedom and a tendency to acquire the fourth one (for meandering) and idealize the natural rivers so well that Prof. Blench calls them the "laboratory of the inductive science of regime theory."

The idea of the study of channel-self-adjustment was first conceived by R. G. Kennedy in 1895. He studied the behaviour of a number of self-adjusted canals in the Indo-Gangetic plains and tried to find a relation between their hydraulic and geometric features and proposed the following relation

$$V = 0.84d^{0.64} \tag{3.2.1}$$

This equation was one step towards the design of mobile-boundary canals which used to be designed by the conventional Manning's formula based on rigid-boundary hydraulics but it could not explain the third degree of freedom of the canal system.

It was Lindley, in 1919, who first proposed the basic principles of regime theory in its present acceptable form. His statement was "when an artificial channel is used to convey silty water, both bed and banks scour or fill, changing depth, gradient, and width, until a state of balance is attained at which the channel is said to be in-regime" (quoted from Blench, Ref. 1). Lindley related both bed-width and

[illegible]

depth with velocity by the following relations

$$V = 0.95(d)^{0.57} \tag{3.2.2.}$$

$$V = 0.57(b)^{0.335} \tag{3.2.3}$$

Gerald Lacey (1929, 1933) proposed a change in earlier regime relations and introduced his silt-factor. He proposed the use of hydraulic radius and wetted perimeters instead of Lindley's breadth and depth but later, Lacey (1958) agreed to use breadth and depth in sectional equations. He also found out a slope-relation using his silt-factor. Lacey's three basic equations may be written:

$$\frac{V^2}{gR} \propto f \tag{3.2.4}$$

$$\frac{P}{R} \propto \frac{V}{(\nu g)^{1/3}} \tag{3.2.5}$$

$$V \propto \left(\frac{VR}{\nu}\right)^{1/6} \times \left(\frac{V^2}{gR}\right)^{-1/3} \times \sqrt{gRS} \tag{3.2.6}$$

corresponding to the three degrees of self-adjustment. N. K. Bose (1936) proposed the use of bed-load size instead of silt-factor. Blench (1941) proposed splitting of Lacey's silt-factor to account for the different natures of unduned and relatively cohesive sides and the non-cohesive duned beds of mobile-boundary channels and introduced his bed-factor and side-factor

$$F_b = \frac{V^2}{d} \tag{3.2.7}$$

$$F_s = \frac{V^3}{b} \tag{3.2.8}$$

He favoured the use of breadth and depth in the sectional equations. King (1943) found, from data analysis, a dynamically satisfying slope equation

$$\frac{V^2}{gd\hat{S}} \propto \left(\frac{Vb}{\nu}\right)^{\frac{1}{4}} \tag{3.2.9}$$

Inglis (1949) emphasized the inclusion of bed-load charge explicitly in the silt-factor. Analysing classical Gilbert data, Blench and Erb (Ref. 5) proposed a modified bed-factor equation to include charge and thus converted King's slope equation (Equation 3.2.9) into a sediment transport one. Blench and Qureshi (1964)(Ref. 27) proposed a design curve for rough estimate of $F_{bo}$ in terms of size of the bed-material, $\nu$ and g.

## 3.3 BED-LOAD TRANSPORT FORMULAS BASED ON REGIME THEORY

All the bed-load formulas and their development as described in section 2.2, with the exceptions of Einstein's and Kalinske's relations are based on the conventional tractive force theory. A major deviation from this approach to the problem is that of regime theory. Regime theory describing, as it does, the characteristics of self-adjusted channels, can be and is applied to the flumes which have adjusted themselves to equilibrium and the theory is, therefore, expected to describe the transport of sediment as observed in flume experiments. Inglis (Ref. 24) made the first

attempt to investigate the effect of quantity or concentration of transported materials on the regime of the channels and produced a relation to include charge in a regime equation as

$$b g^{1/5}/Q^2 = \text{fns}(Q/D^{5/2} g^{\frac{1}{2}})^{n_1} \left(CV_f/(\nu g)^{1/3}\right)^{n_2} \quad (3.3.1)$$

where C = bed-load charge in P.P.H.T.

b = breadth of channel

$\nu$ = kinematic viscosity of fluid

and other terms are as defined earlier. Erb (Ref. 25) disputed the validity of Equation 3.3.1 on the ground that it indicates the channels of infinite depth and zero slope for the important case of vanishingly small charge. On the basis of flume experiments Blench (Ref. 26) suggested that bed-load charge be included in a bed-factor equation

$$F_b = F_{bo} (1+a_1 C) \quad (3.3.2)$$

where $F_b$ = bed-factor = $V^2/d$

$F_{bo}$ = bed-factor for vanishingly small charge and is a function of grain size

C = charge in P.P.H.T.

$a_1$ = a constant.

After analysing Gilbert and others' data Blench and Erb (Ref. 5) proposed a value of 0.12 for "$a_1$" for the condition of sub-critical flow and natural river-bed sand. For super-critical flow a formula

$$F_b = 32.2 + 0.06\ (C - C_c) \qquad (3.3.3)$$

was proposed for Gilbert's uniformised sand. $C_c$ in Eq. 3.3.3 is the charge corresponding to critical velocity. Blench and Erb also modified King's regime slope equation into a transport one

$$V^2/gdS = 3.63\ (1 + C/233)\ (Vb/\nu)^{\frac{1}{4}} \qquad (3.3.4)$$

for sub-critical flow only. Blench and Qureshi (1964) (Ref. 27) suggested, on speculative grounds, a relation

$$F_{bo} = 7.3 \cdot {}_{w}^{m}D^{\frac{1}{4}} \times (\nu_{70}/\nu)^{1/6} \qquad (3.3.5)$$

where $D$ = material size in feet

$\nu_{70}$ = kinematic viscosity at 70°F.

This is believed to be valid for all materials of specific gravity 2.65 and larger than 2 mm. in size. On the same grounds, they also suggested a relation

$$F_{bo} = 0.58\ V_f^{\ 11/24}\ (\nu_{70}/\nu)^{11/72} \qquad (3.3.6)$$

for intermediate sand range. The validity of Equation 3.3.5 is questioned by Neill (Ref. 15 PP. 27) It is important to note that workers in regime theory were aware that their channels worked in a particular phase, so their formulas could not be expected to apply outside of some limits. However, non-dimensional regime theory parameters may be useful outside of these limits.

## 3.4 DIMENSIONAL ANALYSIS

"Dimensional analysis" involves making a dimensional physical statement non-dimensional to ensure the

dimensional homogeneity that is essential in the statement of a physical law. To be of any value, the dimensional statement, to which it is applied, must be the full statement of a phenomenon in the form - "when the following quantities are specified, then the following must depend on them". The greatest advantage of dimensional analysis is that it compels the full physical statement of a problem. Its practical advantage is that it reduces the number of independent variables in a statement to a minimum.

A typical problem of alluvial channels may be dynamically stated in the following words:

"Suppose we have a long straight horizontal flume of breadth b with smooth vertical sides at a place where body force due to gravity is g. A steady uniform discharge Q of fluid with kinematic viscosity $\nu$ and mass density $\rho_f$ flows through the flume along with sediment, believed to move as bed-load, of some representative size D (considered ${}^{m}_{w}D$ in this paper), density $\rho_s$ and non-dimensional properties (size distribution, shapes, their distribution and pattern etc.) X , in quantity which results in a bed-load charge C. It might be possible that the fluid-sediment complex is also charged with suspended load of specific size, shape, density and quantity. But for simplicity, these might be excluded at this

stage. Now, under these conditions, the channel will adjust to equilibrium with

$$\ldots d,\ gS = \text{fns.}(b, C, D, Q, \rho_f, \nu, \rho_s, g, X) \qquad (3.4.1)$$

To the left of Equation 3.4.1, may be added such other dependent variables as dune-height, their wave-length and shear stress. But these are not of immediate interest in this paper. Dimensional analysis can reduce Equation 3.4.1 to

$$V^2/(s-1)gd,\ V^2/gdS = \text{fns.}(d/D,\ C,\ b/d,\ \rho_s/\rho_f, \sqrt[3]{g(s-1)}\frac{D}{\nu}, X) \qquad (3.4.2)$$

The numerics in Equation 3.4.2 can be commented as follows:

| | | |
|---|---|---|
| $V^2/(s-1)gd$ | - | is Blench's bed-factor amended by $(s-1)g$ to allow for "buoyant weight" of sediment. In density current works it is known as "densimetric Froude Number". |
| $V^2/gdS$ | - | is effectively a conventional friction factor. |
| $d/D$ | - | is depth/grain size, so is the reciprocal of what Neill (1966) calls relative grain-size and may also be called relative depth of flow. |
| $C$ | - | is charge in parts per hundred thousand. |

| | | |
|---|---|---|
| b/d | - | is breadth to depth ratio. |
| $\rho_s / \rho_f$ | - | is the specific gravity of bed-material and can be replaced by s. |
| $\sqrt[3]{\nu g(s-1)}\frac{D}{\nu}$ | - | is effectively a Reynolds' Number that Blench calls the VIG Number. Regime theory shows that it is relevant in the region where $(d/D) > 600$ (Ref. 4). |
| X | – | represents non-dimensional properties of the bed-materials as mentioned in the statement of the typical problem. |

3.5 SOURCES AND DESCRIPTIONS OF DATA USED IN THIS ANALYSIS

3.5.1 U.S.W.E.S.:

These data from the experiments carried out by U.S.W.E.S. in Vicksburg, Mississippi, were reported in reference 10. Nine different alleged natural (as reported in the reference) sand-mixtures were used in the flume studies and the rates of movement of various sizes and the tractive forces necessary for the commencement of their movement were studied. It was noted in the paper that no data were recorded for any run until an absolute equilibrium had been reached. But considering the short duration of the runs and considering the long time which is required, as mentioned by Blench (Ref. 26) and Erb (Ref. 25),

by a flow in flume to run to regime, it was quite probable that complete regime was not reached in those experiments. Besides the nine natural sand mixtures U.S.W.E.S. also used a synthetic sand mixture for a series of flume-experiments. The synthetic sand mixture was prepared by mixing together uniform sieve sizes of filter sand previously screened from the natural mixtures of the materials. All the materials used in the experiments were composed of quartz and feldspar particles with small percentage of other minerals. The mechanical analysis curves of these materials are shown in FIGURES C-1 to C-12. The gradation $G_R$ calculated on a method suggested by Simons et al is noted in tables 3.1 and 3.1(a) where other physical characteristics of the materials are also listed. The values of $D_{50}$, $D_{98}$, $D_{84}$, $D_{16}$ and $D_2$ along with the values of $D_{98}/D_{50}$, $D_{84}/D_{50}$ and $D_2/D_{50}$ are shown in table B-1. Table B-1 also lists the values of $D_{98}/D_{50}$, $D_{84}/D_{50}$ and $D_2/D_{50}$ for the Fraser River-sand (B.C.) for comparison with other figures tabulated therein.

In some other experiments U.S.W.E.S. (Ref. 37) used light-weight materials to determine their suitability for use as bed-materials in the models. Porous materials were soaked and stirred until they reached their maximum specific gravity before

TABLE 3-1

SUMMARY TABLE SHOWING GENERAL INFORMATION ABOUT U.S.W.E.S. EXPERIMENTS

| Material Designation used by U.S.W.E.S. | Flume Breadth in Ft. | Median Diameter mm. | Median Diameter ft.x$10^3$ | Type of Material | Classification of Material | Specific Gravity | Shapes of Particles | Gradation $G_R=\frac{1}{2}\left(\frac{D_{84}}{D_{50}}+\frac{D_{50}}{D_{16}}\right)$ |
|---|---|---|---|---|---|---|---|---|
| Sand No. 1 | 2.415 | 0.420 | 1.378 | River Sand From Mississippi Or From Deposit near Vicksburg | Natural Mixture | 2.65 | Sub-angular to Sub-rounded | 1.89 |
| 2 | 2.415 | 0.450 | 1.47 | " | " | 2.65 | " | 1.51 |
| 3 | 2.313 | 0.476 | 1.558 | " | " | 2.65 | Sub-rounded to rounded | 1.37 |
| 4 | 2.313 | 0.436 | 1.43 | " | " | 2.65 | Angular to Sub-rounded | 1.70 |
| 5 | 2.313 | 0.400 | 1.312 | " | " | 2.65 | Sub-angular to angular | 1.62 |
| 6 | 2.415 | 0.320 | 1.050 | " | " | 2.65 | Sub-rounded to sub-angular | 1.22 |
| 7 | 2.415 | 0.283 | 0.930 | " | " | 2.65 | " | 1.42 |
| 8 | 2.313 | 0.181 | 0.594 | " | " | 2.65 | Sub-angular to angular | 1.30 |
| 9 | 2.313 | 4.10 | 13.451 | " | " | 2.65 | Sub-rounded to sub-angular | 1.40 |
| 10 | 2.313 | 0.95 | 3.117 | " | Synthetic Mixture | 2.65 | Sub-angular to angular | 1.39 |

TABLE 3-1 (a)

SUMMARY TABLE SHOWING GENERAL INFORMATION ABOUT U.S.W.E.S. EXPERIMENTS WITH SYNTHETIC MIXTURES

| Material Designation used by U.S.W.E.S. | Flume Breadth in Ft. | Median Diameter mm. | Median Diameter ft.x$10^3$ | Type of Material | Classification of Material | Specific Gravity | Shapes of Particles | $G_R$ |
|---|---|---|---|---|---|---|---|---|
| $U_{.293}$ | 1.00 | 0.36 | 1.181 | River Sand | Unigranular | 2.65 | Sub-angular to angular | 1.15 |
| $U_{.417}$ | " | 0.48 | 1.575 | " | " | 2.65 | " | 1.10 |
| $U_{.589}$ | " | 0.67 | 2.198 | " | " | 2.65 | " | 1.10 |
| $U_{.833}$ | " | 0.94 | 3.084 | " | " | 2.65 | " | 1.11 |
| A | " | 0.77 | 2.526 | " | Synthetic Mixture | 2.65 | " | 1.21 |
| B | " | 0.66 | 2.165 | " | " | 2.65 | " | 1.30 |
| D | " | 1.03 | 3.379 | " | " | 2.65 | " | 1.14 |
| E | " | 0.88 | 2.887 | " | " | 2.65 | " | 1.08 |
| F | " | 1.08 | 3.543 | " | " | 2.65 | " | 1.44 |
| G | " | 0.90 | 2.953 | " | " | 2.65 | " | 1.33 |
| H | " | 0.96 | 3.15 | " | " | 2.65 | " | 1.55 |
| I | " | 0.94 | 3.084 | " | " | 2.65 | " | 1.68 |
| J | " | 0.90 | 2.953 | " | " | 2.65 | " | 1.75 |
| K | " | 0.725 | 2.379 | " | " | 2.65 | " | 1.30 |
| L | " | 0.63 | 2.067 | " | " | 2.65 | " | 1.56 |
| M | " | 0.69 | 2.264 | " | " | 2.65 | " | 1.62 |
| Filter Sand | " | 0.45 | 1.476 | River Sand | Natural Mixture | 2.65 | " | 1.81 |

[illegible]

TABLE 3-1 (b)

SUMMARY TABLE SHOWING GENERAL INFORMATION ABOUT U.S.W.E.S. EXPERIMENTS WITH LIGHT WEIGHT MATERIALS

| Material Designation used by U.S.W.E.S. | Flume Breadth in Ft. | Median Diameter mm. | Median Diameter $ft. \times 10^3$ | Type of Material | Classification of Material | Specific Gravity of Material | Shapes of Grains.. |
|---|---|---|---|---|---|---|---|
| $H_1$ | 1.00 | 0.90 | 2.96 | Haydite | Commercial Mixture | 1.85 | Angular |
| $H_2$ | 1.00 | 0.83 | 2.70 | " | " | 1.85 | " |
| $H_3$ | 1.00 | 1.20 | 3.90 | " | " | 1.74 | " |
| $C_1$ | 1.00 | 4.0 | 13.10 | Coal | Mixture resulting from crushing | 1.35 | " |
| $C_2$ | 1.00 | 1.0 | 3.28 | " | " | 1.35 | " |
| $C_3$ | 1.00 | 2.95 | 9.70 | " | " | 1.32 | " |
| $C_4$ | 1.00 | 1.50 | 4.90 | " | " | 1.32 | " |
| $C_5$ | 1.00 | 1.90 | 6.20 | " | " | 1.31 | " |
| $C_6$ | 1.00 | 1.16 | 3.80 | " | " | 1.31 | " |
| $C_8$ | 1.00 | 0.90 | 2.96 | Flake Pitch | " | 1.26 | " |
| $R_1$ (Helix-1 limed) | 1.00 | 2.25 | 7.40 | Resin (Helix-1 limed) | " | 1.11 | " |

placement. The general information about these materials is shown in table 3.1(b). The grain size distribution curves for each material are shown in FIGURES C-36 to C-38.

### 3.5.2 T. Y. LIU

T.Y. Liu (Ref. 30) collected these data at the University of Iowa Institute of Hydraulic Research. For incipient (initiation) condition, depth, slope and rate of flow and velocity distributions were recorded. The rate of bed-load transporation were also measured. The material used was commercial sand collected from the Iowa River at Iowa city. This could have been a mixture of natural sands of different $D_{50}$. The grain-size distribution curves are shown in FIGURES C-13 and C-14 and the values of $D_{50}$, $D_{98}$, $D_{84}$, $D_{16}$ and $D_{2}$ for each material are noted in table B-1. The physical properties of the materials are listed in table 3.2.

TABLE 3-2

SUMMARY TABLE SHOWING THE PHYSICAL PROPERTIES OF MATERIALS IN

T.Y. LIU EXPERIMENTS

| Material Designation used by Liu | Flume Breadth in ft. | Median Diameter | | Type of Material | Classification of Material | Specific Gravity | Shape of Particles | $G_R$ |
|---|---|---|---|---|---|---|---|---|
| | | mm. | ft.x$10^3$ | | | | | |
| I | 2.688 | 4.30 | 14.1 | River Sand | Graded sand (by screening) | 2.66 | Rounded | 1.16 |
| II | 2.688 | 3.25 | 10.66 | " | " | 2.66 | " | 1.10 |
| III | 2.688 | 2.26 | 7.42 | " | " | 2.66 | " | 1.13 |
| IV | 2.688 | 1.48 | 4.85 | " | " | 2.66 | " | 1.22 |
| V | 2.688 | 3.60 | 11.8 | " | Mixture of I & II | 2.66 | " | 1.21 |
| VI | 2.688 | 1.70 | 5.58 | " | Mixture of III & IV | 2.66 | " | 1.35 |

### 3.5.3 COLORADO STATE UNIVERSITY

Guy, Simons and Richardson presented these data in U.S.G.S. professional paper 462-I (Ref. 31). The experiments were carried out in the hydraulics laboratory of Colorado State University during the years 1956-61. The purpose of the experiments was to determine the effects of the size of the bed-materials, temperature of water and the fine sediment in the flow on the transport phenomenon. Each set of experiments covered transport phases ranging from a plane bed and no sediment movement to violent antidunes. The sands used as bed-material were collected from five different natural streams. The general information about the materials is shown in Table 3.3 and the grain size distribution curves are shown in FIGURES C-15 to C-17. From the distribution curves shown for six different materials, it appears that only three (median diameter 0.19, 0.45, and 0.47 mm.) materials follow approximately the log-normal distribution found in natural river-bed. The other one (0.27 mm. median dia.) follows log-normal distribution approximately. The values of $D_{50}$, $D_{98}$, $D_{84}$, $D_{16}$ and $D_2$ for individual material are noted in Table B-1. Photographs of each sand showing their shapes, gradation and relative sizes are reproduced in FIGURE 3.5.1.

TABLE 3-3

SUMMARY TABLE SHOWING GENERAL INFORMATION ABOUT C.S.U. EXPERIMENTS

| Flume Breadth in Ft. | Median Diameter mm. | Median Diameter ft.x$10^3$ | Type of Material | Classification of Material Used | Specific Gravity of Materials | Shape of Grains | $G_R$ |
|---|---|---|---|---|---|---|---|
| 8.0 | 0.19 | 0.623 | Decomposed sandstone near Denver. | Sandstone crushed and washed to remove clay binder. | 2.65 | Shown in Figure 3.5.1 | 1.30 |
| 8.0 | 0.27 | 0.886 | River Sand | Natural mixture | 2.65 | " | 1.56 |
| 8.0 | 0.28 | 0.919 | " | " | 2.65 | " | 1.67 |
| 8.0 | 0.45 | 1.476 | " | " | 2.65 | " | 1.60 |
| 8.0 | 0.47 | 1.542 | " | " | 2.65 | " | 1.54 |
| 8.0 | 0.93 | 3.051 | " | (Seived and washed) Natural Mixture | 2.65 | " | 1.54 |
| 2.0 | 0.32 | 1.05 | River sand | From 0.27 mm. Sand Coarser sand retained and fines were washed away in overflow. | 2.65 | " | 1.57 |
| 2.0 | 0.33U | 1.083 | Commercial Sand | Seived. | 2.65 | " | 1.25 |
| 2.0 | 0.33G | 1.083 | " | Seived. | 2.65 | " | 2.07 |
| 2.0 | 0.54 | 1.772 | River Sand | From 0.45 mm. Sand Processed. | 2.65 | " | 1.52 |

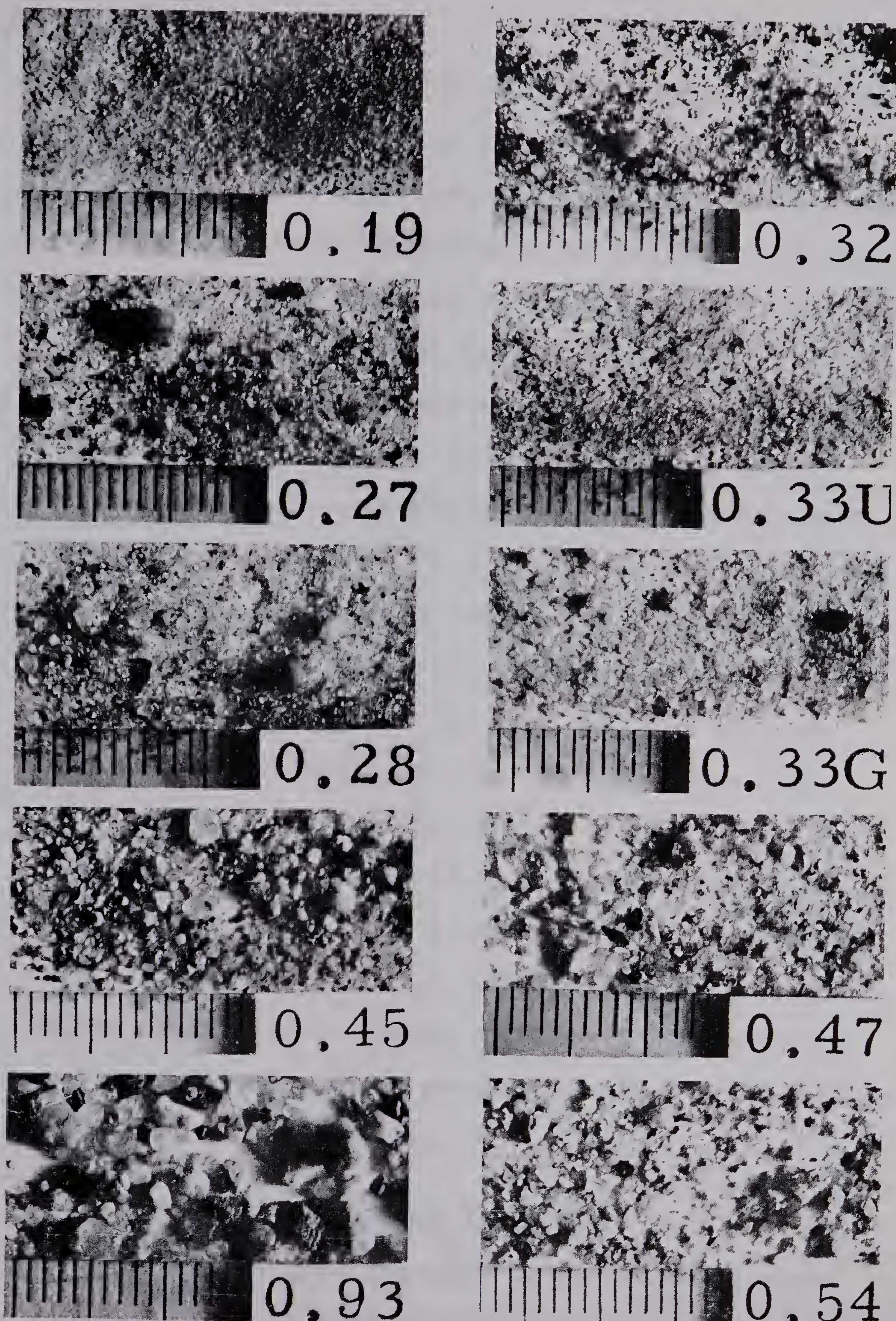



FIGURE 3-5-1 PHOTOGRAPHS SHOWING SHAPES OF SAND PARTICLES USED IN C.S.U. EXPERIMENTS. THE NUMBER IN THE LOWER RIGHT CORNER OF EACH PHOTOGRAPH IS THE MEDIAN DIAMETER OF SAND, IN MILLIMETERS.

### 3.5.4 BHARAT SINGH

Bharat Singh (Ref. 36) described the studies made (up to 1960) in this field by various investigators. In his own flume experiments in the Hawksley hydraulics laboratory, London, he collected a set of data on bed-load transport. His flume was 23 ft. long and 2.5 ft. wide. Beach sand obtained from commercial suppliers was used as bed-material. The grain size distribution curve from the sieve analysis of the materials is shown in FIGURE C-18. Almost 80% of the sands were between 0.5 to 0.75 mm. in size. The size distribution curve is in reasonable agreement with the log-normal distribution found in the natural river bed. The specific gravity of the sand was 2.64 and the average fall velocity in water at $14^{\circ}$ c. was 6.93 cm./sec. The shape of the grains was fairly well-rounded. The time allowed to each run to reach to regime varied from 1 to 6 hours. The depth of flow was adjusted to be uniform and the flow was assumed to be in equilibrium. Regime conditions were probably not established yet the results show a good accordance with others in this study.

### 3.5.5 WEST BENGAL RIVER RESEARCH INSTITUTE

These data reported in Reference 32 were collected in a tilting flume 85' long and 1.5 ft. wide. The depth of mobile bed was 0.5 ft. and the sides were

of glass. Uniform flow was established by adjusting the tail gate. Sieved sand in the range of 0.15 to 0.5 mm. in diameter was used as bed-material. The grain size distribution curve from the mechanical analysis of the material is shown in FIGURE C-19. The values of $D_{50}$, $D_{98}$, $D_{84}$, $D_{16}$ and $D_2$ are noted in Table B-1.

### 3.5.6 BHATTACHARYA

Bhattacharya (1960) (Ref. 33) carried out flume experiments in the hydraulics laboratory of the University of Alberta to discover whether bed-factor was anomalous when transport occurs in sub-critical flow without dunes. The experimental flume was 12 inches wide, 18 feet long and 2'-6" deep. Experiments were carried out both with charge and without charge. The range of water-discharge for runs without charge was from 0.32 cusec. to 1.246 cusecs. and the range of flow depth was from 2.0 inches to 11 inches. Thus the ratio of b/d ranges from 1.09 to 4.0 only but, of course, the experiments were not expected to give the values of bed-factor for larger b/d ratios. Considering these factors the data were found useful for testing the effect of b/d on the analysis of this study. Bhattacharya considered most of the runs without charge as those of $F_{bo}$-condition but some of these appear to be of initiation-condition. The

individual runs were allowed 6 to 60 hours to have the working regime conditions established. The material used as bed-load was 1.7 mm. in median diameter before the experiment and 1.73 mm. after the experiment. The mechanical analysis curve of the material is shown in FIGURE C-20. The values of $D_{50}$, $D_{98}$, $D_{84}$, $D_{16}$ and $D_2$ as well as the value of $G_R$. are noted in Table B-1.

### 3.5.7 DATA COLLECTED BY M. A. QURESHI

Qureshi (1962) (Ref. 34) virtually repeated Bhattacharya's experiments in a larger flume. The material used was the same as that used by Bhattacharya. The runs were allowed 15 to 72 hours of time to reach to regime. The ranges of various variables in Qureshi's experiments are shown in Table B-2.

### 3.5.8 OTHER DATA ANALYSED IN THIS PAPER

Flume data related to bed-load transport were collected independently by H. J. Casey, M. P. O'Brien, J. Bogardi & C. H. Yen, Ho Pang Yung, A. L. Jorissen, C. H. MacDougall, G. K. Gilbert, E. Meyer-Peter & Muller, and Barton & Lin. But only small groups of their data fall within the scope of this paper and have been used in this analysis. A brief description of their experiments is given in Table 3.4. The mechanical analysis curves of the materials are shown in FIGURES C-21 to C-33. The values of $D_{50}$, $D_{98}$, $D_{84}$, $D_{16}$, $D_2$, $D_{98}/D_{50}$,

TABLE 3-4

SUMMARY OF PHYSICAL PROPERTIES OF THE MATERIALS USED BY VARIOUS OTHER INVESTIGATORS WHOSE DATA HAVE BEEN ANALYSED IN THIS PAPER

| Name of authors and year of study | Designation of materials as used by authors | Flume Breadth Ft. | Median Diameter mm. | Median Diameter ft.x$10^3$ | Type of Material | Classification of Material | Specific Gravity | Shape of Particles | $G_R$ |
|---|---|---|---|---|---|---|---|---|---|
| H. J. Casey (1935) | h | 1.312 | 2.26 | 7.41 | Sand | Uniform | 2.65 | Subangular to rounded | 1.07 |
| | III a | 1.312 | 1.20 | 3.94 | Sand | Synthetic Mixture | 2.65 | " | 4.53 |
| Ho Pang Yung (1939) | I | 1.312 | 3.00 | 9.84 | Gravel (from river) | Synthetic mixture prepared by sieving | 2.58 | Flat | 1.88 |
| | II | 1.312 | 4.30 | 14.11 | " | " | 2.58 | " | 1.57 |
| | III | 1.312 | 6.10 | 20.01 | " | " | 2.58 | " | 1.49 |
| | IV | 1.312 | 1.30 | 4.27 | " | " | 2.58 | " | 1.71 |
| | V | 1.312 | 6.00 | 19.69 | " | " | 2.58 | " | 1.30 |
| | VI | 1.312 | 1.45 | 4.75 | Sand (Quartz) | " | 2.65 | Rounded | 1.78 |
| Meyer-Peter (1948) | 1 | 3.28 | 28.6 | 93.99 | Gravel | Uniform | 2.65 | Well rounded | |
| | 2 | 3.28 | 5.2 | 17.09 | " | " | 2.65 | " | |
| | 3 | 3.28 | 3.3 | 10.83 | " | " | 2.65 | " | |
| (Material | 4 | 3.28 | 2.7 | 8.86 | " | " | 2.65 | | |
| designated | 5 | 3.28 | 4.05 | 13.22 | " | " | 2.65 | | |
| by this author | 6 | 3.28 | 1.5 | 4.92 | " | " | 2.65 | | |
| according to | 7 | 3.28 | 1.17 | 3.84 | " | " | 2.65 | | |
| material size) | 8 | 3.28 | 1.00 | 3.28 | " | " | 2.65 | | |
| | 9 | 3.28 | 0.40 | 1.312 | " | " | 2.65 | | |

TABLE 3-4 (CONTINUED)

| Name of authors and year of study | Designation of materials as used by authors | Flume Breadth Ft. | Median Diameter mm. | Median Diameter ft.x$10^3$ | Type of Material | Classification of Material | Specific Gravity | Shape of Particles | $G_R$ |
|---|---|---|---|---|---|---|---|---|---|
| M. P. O'Brien (1936) | - | 3.0 | 0.36 | 1.181 | River Sand | Natural Mixture | 2.57 | Sub-angular | 1.48 |
| H.A. Einstein | - | 16.0 | 0.90 | 2.95 | " | " | | | 1.84 |
| Bogardi & Yen | 1 | 2.75 | 10.0 | 32.8 | Gravel | Uniform | 2.63 | Well-rounded | 1.06 |
| | 3 | 1.00 | 15.0 | 49.2 | Gravel | " | 2.61 | " | 1.04 |
| U.B.C. | 0.31 | 0.682 | 0.31 | 1.017 | - | | | | 1.51 |
| | 0.197 | 0.682 | 0.197 | 0.646 | - | | | | 1.47 |
| MacDougall (1933) | II | 2.0 | 0.93 | 3.051 | Beach Sand | Synthetic Mixture | 2.69 | Rounded | 1.46 |
| A.L. Jorissen (1938) | I | 2.0 | 0.60 | 1.97 | " | " | 2.67 | - | 1.78 |
| | II | 2.0 | 0.87 | 2.86 | " | " | 2.67 | - | 1.43 |
| Gilbert (1914) | B | 0.23-1.96 | 0.375 | 1.23 | River Sand | Uniform | 2.69 | Sub-angular | |
| | C | " | 0.506 | 1.66 | " | " | 2.69 | " | |
| | D | " | 0.786 | 2.58 | " | " | 2.69 | " | |
| | E | " | 1.71 | 5.61 | " | " | 2.69 | sub-rounded | |
| Barton & Lin | - | 4.0 | 0.18 | 0.591 | - | - | 2.65 | - | 1.26 |

$D_{84}/D_{50}$, $D_2/D_{50}$ along with the values of $G_R$ for each of the material used by them are given in Table B-1. A more detailed description of their experimental set-ups will be found in Reference 28.

3.5.9 DATA FROM INITIATION OF MOTION STUDY BY NEILL (Ref. 40)

These experiments to determine velocities of flow required to cause "first displacement" of single stone at various depths of flow were carried out in the hydraulics laboratory of the University of Alberta in 1966. The materials used in the experiments were uniform in grain-size ranging from 5 to 30 mm. in effective diameter. The flow condition was uniform and fully rough. Considering the limited width of the flume available the depth of flow was restricted so that the b/d ratio exceeds the roughly stated value of 5 so that there is a mid-central zone in the flow where the vertical velocity profile is the same as in an infinitely wide channel. The physical properties of the materials are shown in Table 3.5. FIGURE 3.5.2 shows a composite picture of various materials used in the experiment. Neill also provided in the same report some comparable previous laboratory data collected by various investigators. The general information about these data, as provided by him. is also listed in the table.

TABLE 3-5

SUMMARY TABLE SHOWING THE PHYSICAL PROPERTIES OF MATERIALS

USED BY C.R. NEILL AND OTHER COMPARABLE DATA HE PROVIDED

| Material Designation used by Neill | Flume Breadth in Ft. | Effective Diameter *1 mm. | Effective Diameter *1 ft. | Type of Material | Specific Gravity of Material | Classification of Material | Particle Shape Ratio *2 b'/a' | Particle Shape Ratio *2 c'/b' |
|---|---|---|---|---|---|---|---|---|
| A | 3.0 | 8.5 | 0.0278 | Gravel | 2.52 | Uniform | 0.734 | 0.788 |
| B | 3.0 | 10.6 | 0.0348 | Gravel | 2.54 | Uniform | 0.770 | 0.691 |
| C | 3.0 | 20.0 | 0.0656 | Gravel | 2.52 | Uniform | 0.697 | 0.668 |
| D | 3.0 | 6.2 | 0.0203 | Gravel | 2.54 | Uniform | 0.681 | 0.885 |
| G | 3.0 | 5.0 | 0.0164 | Glass balls | 2.49 | Uniform | Round | |
| J | 3.0 | 6.4 | 0.0210 | Cellulose Acetate balls | 1.31 | Uniform | Round | |

| | | | | | | Comments |
|---|---|---|---|---|---|---|
| Mavis, Ho & Tu 1935 | 2.50 | 2.8<br>4.0<br>5.7 | 0.0092<br>0.0131<br>0.0187 | 2.65 | Uniform | width to depth ratio less than 5.0 |
| Linnton Hyd. Lab. 1938 | 6.0 | 8.0<br>11.0<br>16.0<br>32<br>upto 140 | 0.026 to 0.459 | 2.62 to 2.76 | Uniform | Width to Depth ratio more than 4 |
| Meyer-Peter and Muller | 3.28 | 2.6-8.5 | 0.0085 to 0.0279 | 2.68 | Uniform | width to depth ratio greater than 5.0 |

TABLE 3-5 (CONTINUED)

*1 - Adopted effective size for each gravel represents a compromise between the average values of (i) equivalent spherical diameter, (ii) intermediate axis b′, and (iii) mean sieve size.

*2 - a′, b′, c′ - are long, intermediate and short axis of an irregularly-shaped stone.

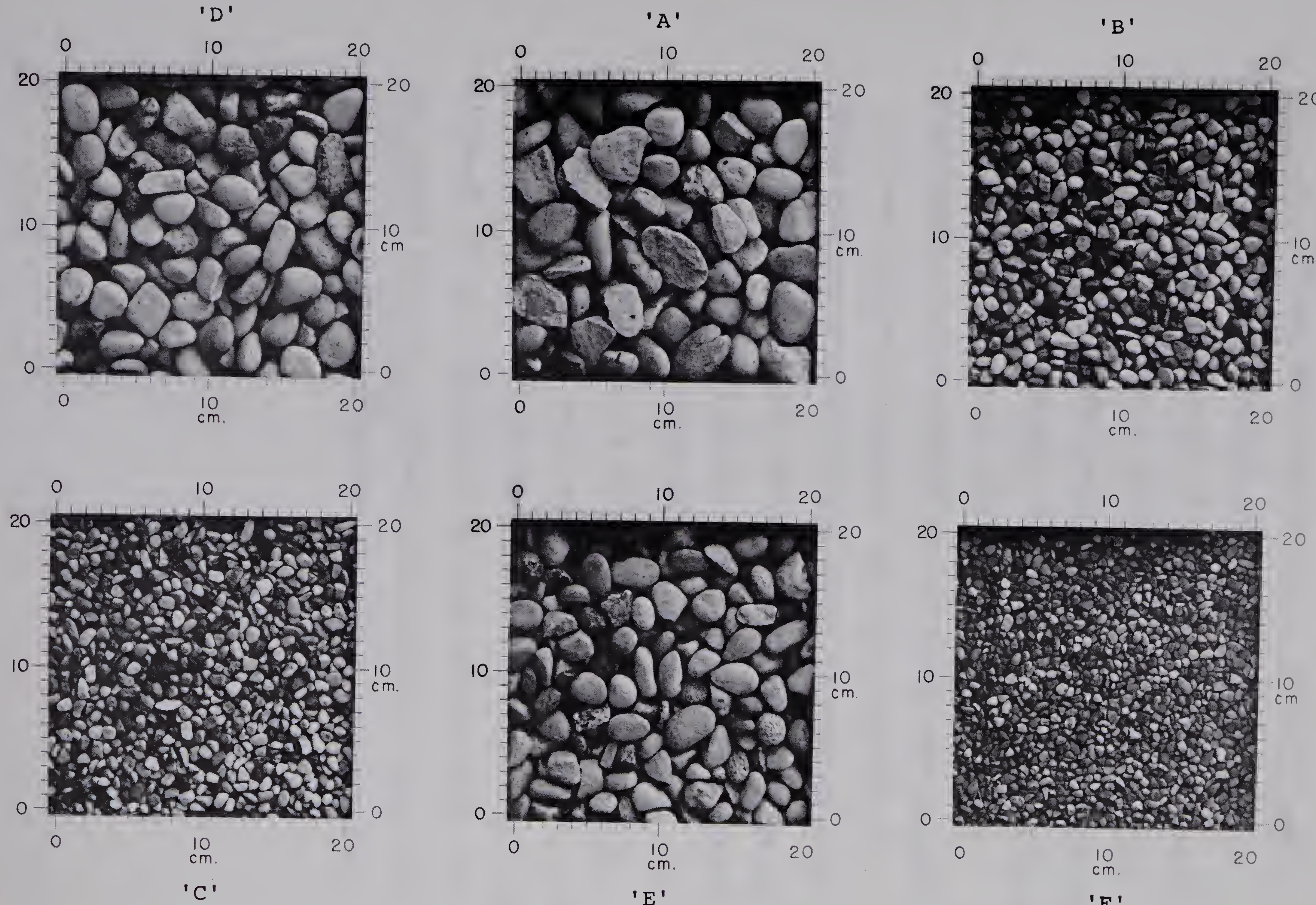



FIGURE 3-5-2 PHOTOGRAPHS SHOWING VARIOUS MATERIALS USED BY C. R. NEILL.

### 3.5.10 ELBOW-RIVER DATA

These data reported by A. B. Hollingshead (Ref. 35) were collected in a joint field project sponsored by Government of Alberta, Research Council of Alberta, University of Alberta and Water Survey of Canada. The study reach was on the Elbow River at Bragg Creek near Calgary. Besides the general hydraulic survey of the river including slope and velocity observation, bed-materials of the river were sampled in three different methods. The size analysis of seven samples of bed-load are shown in FIGURES C-34 and C-35. The points plotted are fitted with approximate straight lines indicating a logarithmic normal distribution. For calculation in this analysis the average ${}_{w}^{m}\bar{D}$ was taken as 0.1 ft. The values of $D_{98}$, $D_{84}$, $D_{16}$ and $D_2$ for each sample are noted in Table B-1. The specific gravity of the material was taken as 2.65 although it was reported to be 2.64 in reference 35. The ranges of other variables are noted in Table B-2. The observed flow parameters are shown in table D-1.

CHAPTER IV

RESULTS AND THEIR DISCUSSIONS

## 4.1 REDUCTION OF ANALYSIS TO SUIT DATA OF THIS PAPER

The functional relation

$$\frac{V^2}{(s-1)gd} = \text{fns.}\left(\frac{d}{D},\ C,\ \frac{b}{d}, \sqrt[3]{(\upsilon g(s-1))}\frac{D}{\upsilon}, \frac{\rho_s}{\rho_f},\ X\right) \qquad (3.4.2)$$

shows that the problem (obviously a flume-transport one) is at least seven dimensional in nature and the analysis investigating the exact nature of relationship between the variables is a complicated one. To simplify the analysis some of the variables are treated as follows:

1. C - the relatively simple case of low charge, C is considered. Tentatively, a value of C up to 10 parts per $10^5$ is considered as low charge. To see how C affects the analysis, this range of C (0-10 P.P.H.T.) is divided into three sub-ranges of C=0-2 P.P.H.T., $2 \leq C \leq 5$ P.P.H.T. and $5 \leq C \leq 10$ P.P.H.T.

2. $\frac{b}{d}$ - considering the general belief that - when $b/d > 5$, the flow phenomenon in the central zone represents that of an infinitely

wide channel - the analysis in the first stage is confined to those experimental data for which $b/d > 5$. In the second stage, to investigate the effect of b/d, all data with any value of b/d are taken and they are divided into four groups according to their b/d values of 0-2, $2 \angle b/d \underline{\angle} 5$, $5 \angle b/d \underline{\angle} 10$ and $b/d > 10$.

3. $\frac{\rho_s}{\rho_f}$ - is essentially the specific gravity of the solid and the speculation was that $\rho_s/\rho_f$ might be removed from its independent status in Equation 3.4.2 if the buoyant weight of bed-load is considered and g is replaced by (s-1)g.

Equation 3.4.2. then reduces to

$$\frac{V^2}{(s-1)gd} = \text{fns.}\left(\frac{d}{D}, \frac{\sqrt[3]{\nu g(s-1)}}{\nu}\frac{D}{\nu}, \frac{\rho_s}{\rho_f}, X, C_1, \left(\frac{b}{d}\right)_1\right) \qquad (4.1)$$

where $C_1$ and $(b/d)_1$ now represent certain ranges of the variables C and b/d respectively. From the world-data available upto date, mostly from the collection of Prof. A. W. Peterson and Mr. R. H. Cooper (Ref. 29) the parameters in Equation 4.1 were calculated on a IBM-360 computer. $V^2/(s-1)gd$ is then plotted against $d/{}_{\nu}^{m}D$ on a double-log paper for the data collected by individual author. These plots of

data of individual author are then superimposed to study the overall nature of the functional relation in Equation 4.1. The plots are discussed in the next article.

## 4.2 DISCUSSION OF THE ANALYSIS

Practical difficulties have prevented the extensive study of all the relevant parameters in Equation 4.1. But some sensible picture of behaviour of $V^2/(s-1)gd$ in sub-critical flow and within the limitation of article 4.1 is indicated in FIGURES 4.1 to 4.3. FIGURE 4.1 is a plot of $V^2/(s-1)gd$ Vs. $d/{}_{v}^{m}D$ for a range of C = 0-2 P.P.H.T. and $b/d \geq 5$. It is obtained by combining FIGURES A-1 to A-6 (Appendix "A"). FIGURES A-1 to A-5 show the plots of the same parameters and for same range of C and b/d as in FIGURE 4.1 but, for individual authors' data showing points representing various materials used in the experiments. FIGURE A-6 is a plot of several authors' data named in the figure itself. Although the plotted points in FIGURE 4.1 show some scatter, they indicate a general trend in the behaviour of $V^2/(s-1)gd$ within the reasonable width of a band. This trend is discussed in the latter part of this article.

FIGURE 4.2 is a plot of $V^2/(s-1)gd$ Vs. $d/{}_{v}^{m}D$ for a range of $2 < C \leq 5$ P.P.H.T. and $b/d \geq 5$.

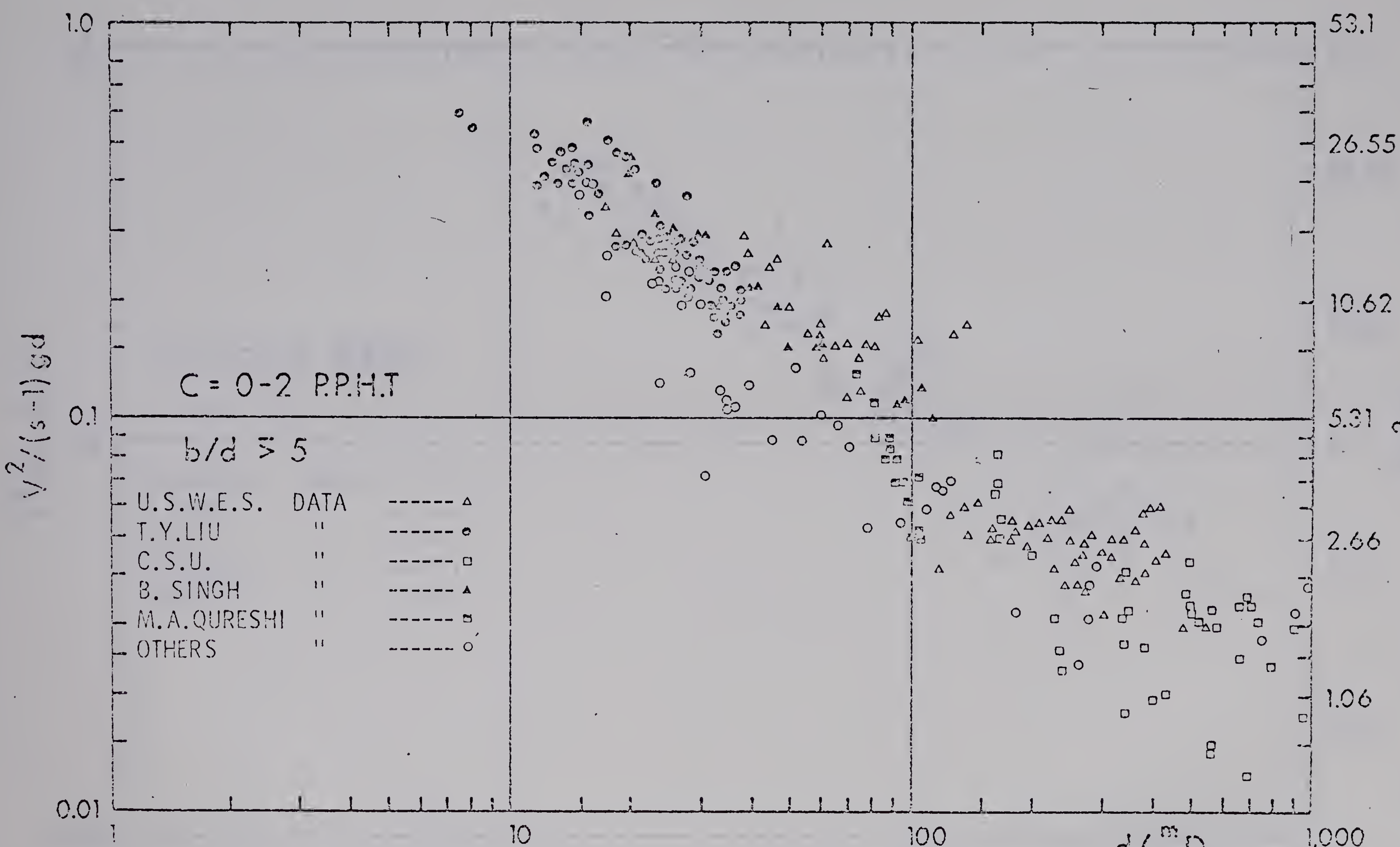



FIG. 4-1 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$

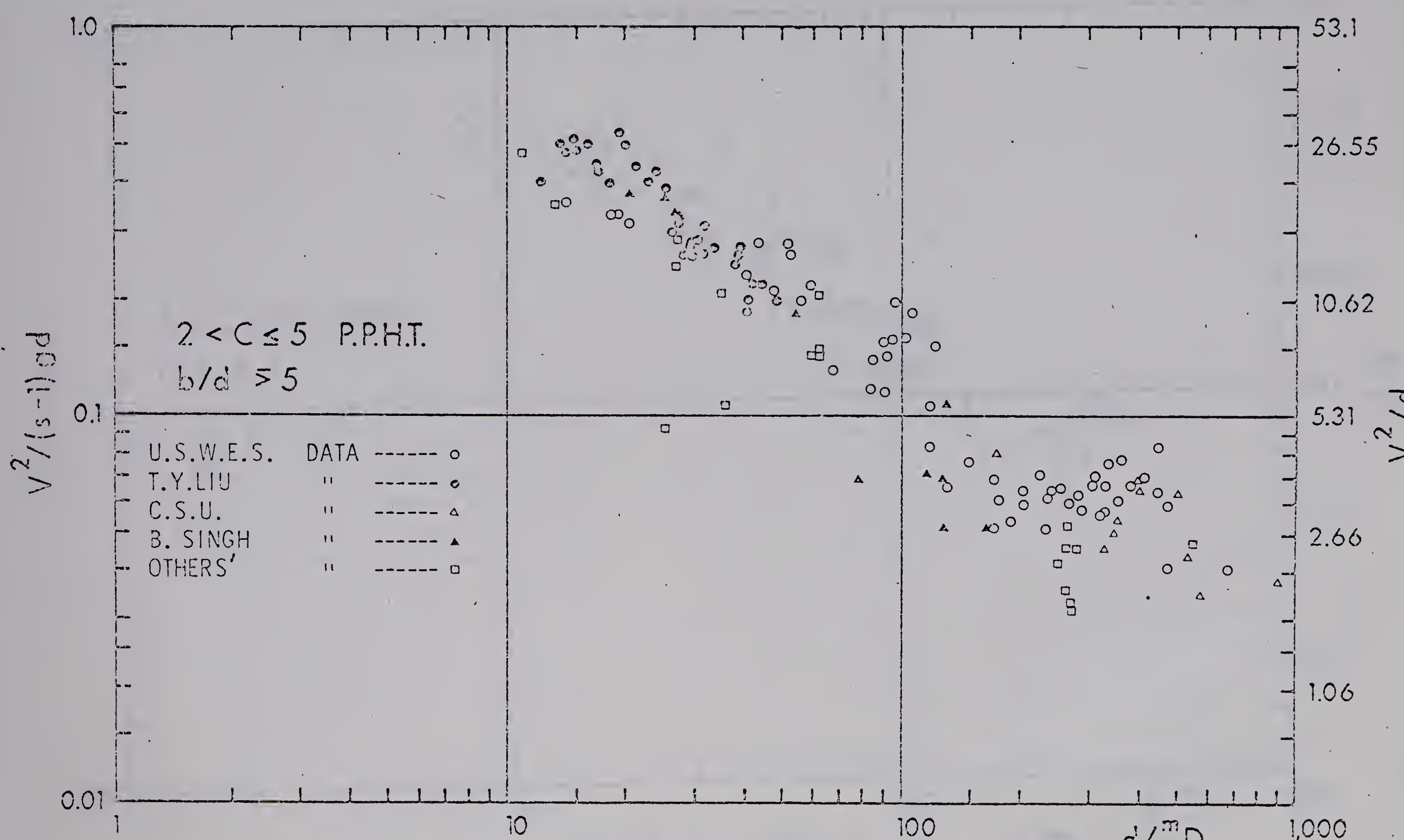



FIG. 4-2 PLOT OF $V^2/(s-1)\,gd$ vs. $d/^m_w D$

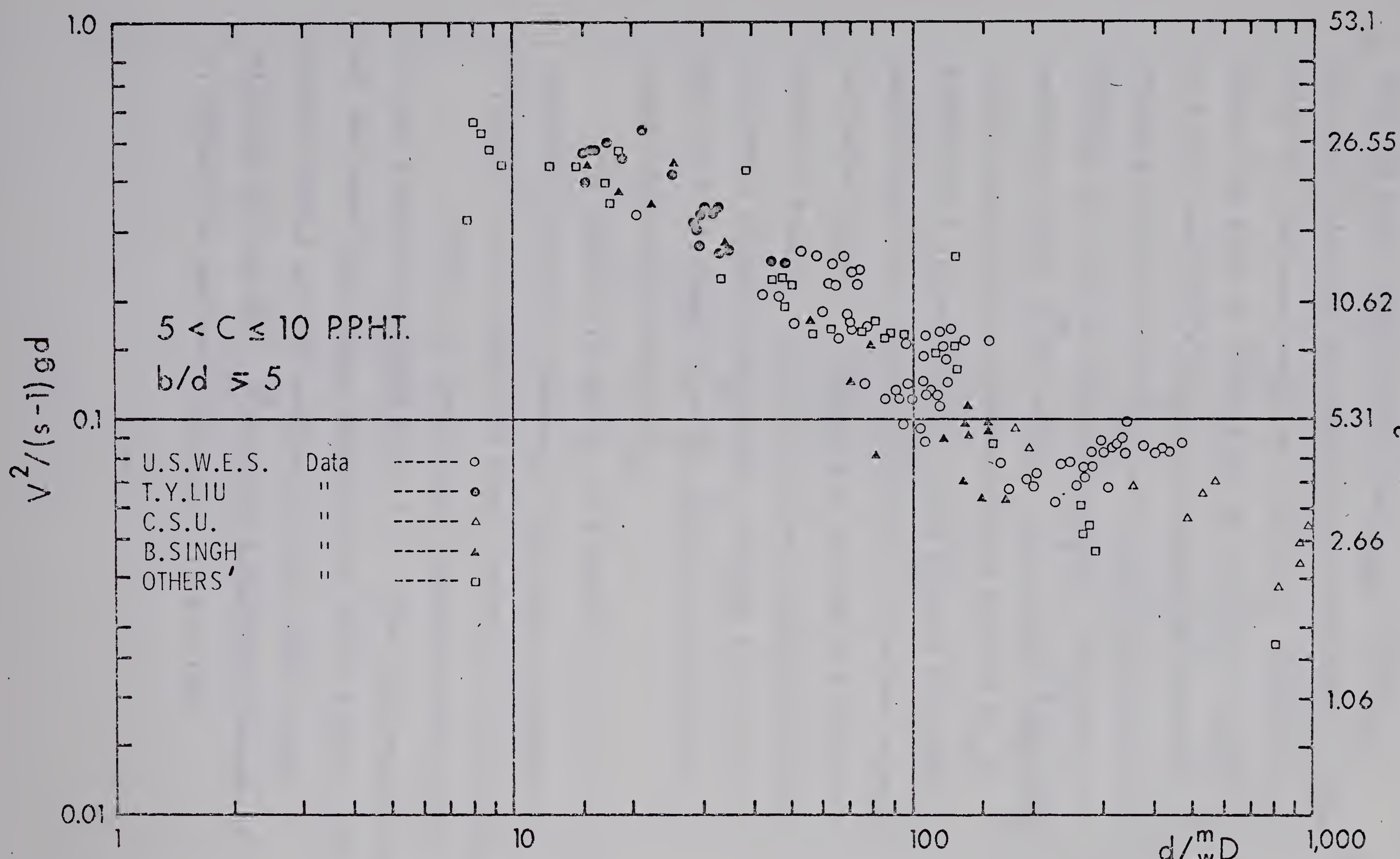



FIG. 4-3 PLOT OF $V^2/(s-1)\,gd$ vs. $d/^m_w D$

This is again obtained by combining FIGURES A-7 to A-11 which are in turn plots of individual authors' data for the same range of C and b/d. FIGURE 4.3 shows the plot of $V^2/(s-1)gd$ Vs. $d/{}_{w}^{m}D$ for $5 < C \leq 10$ P.P.H.T. and $b/d \geqslant 5$ and is obtained by combining FIGURES A-12 to A-16 which are again counterparts of FIGURES A-7 to A-11 but with $5 < C \leq 10$. To study how material sizes $({}_{w}^{m}D)$ and for that matter $\sqrt[3]{\nu g(s-1)}\frac{D}{\nu}$ affect the relation between $V^2/(s-1)gd$ and $d/{}_{w}^{m}D$, FIGURES 4.4 (a) and 4.4 (b) were plotted with data subdivided into various ranges of ${}_{w}^{m}D$ values as noted in these figures. FIGURES 4.5 (a) and 4.5 (b) are plots of similar type but with data subdivided into different ranges of $G_R$ values. FIGURE 4.5 (c) is a plot of H. J. Casey data who used two materials of quite different gradation $G_R$.

Scatter of points in FIGURES 4.4 (a) to 4.5 (c) prevents a definite statement about the dependence of $V^2/(s-1)gd$ on the particle sizes and their distribution.

FIGURE 4.6 shows bands containing about 95% of the points of FIGURES 4.1, 2, 3. The flattened bottoms of the bands suit known behaviour of $V^2/(s-1)gd$ in irrigation canals and are consistent with these points although not proved. $V^2/(s-1)gd$ apparently depends on C, perhaps in proportion to about $(1 + 0.10C)$.

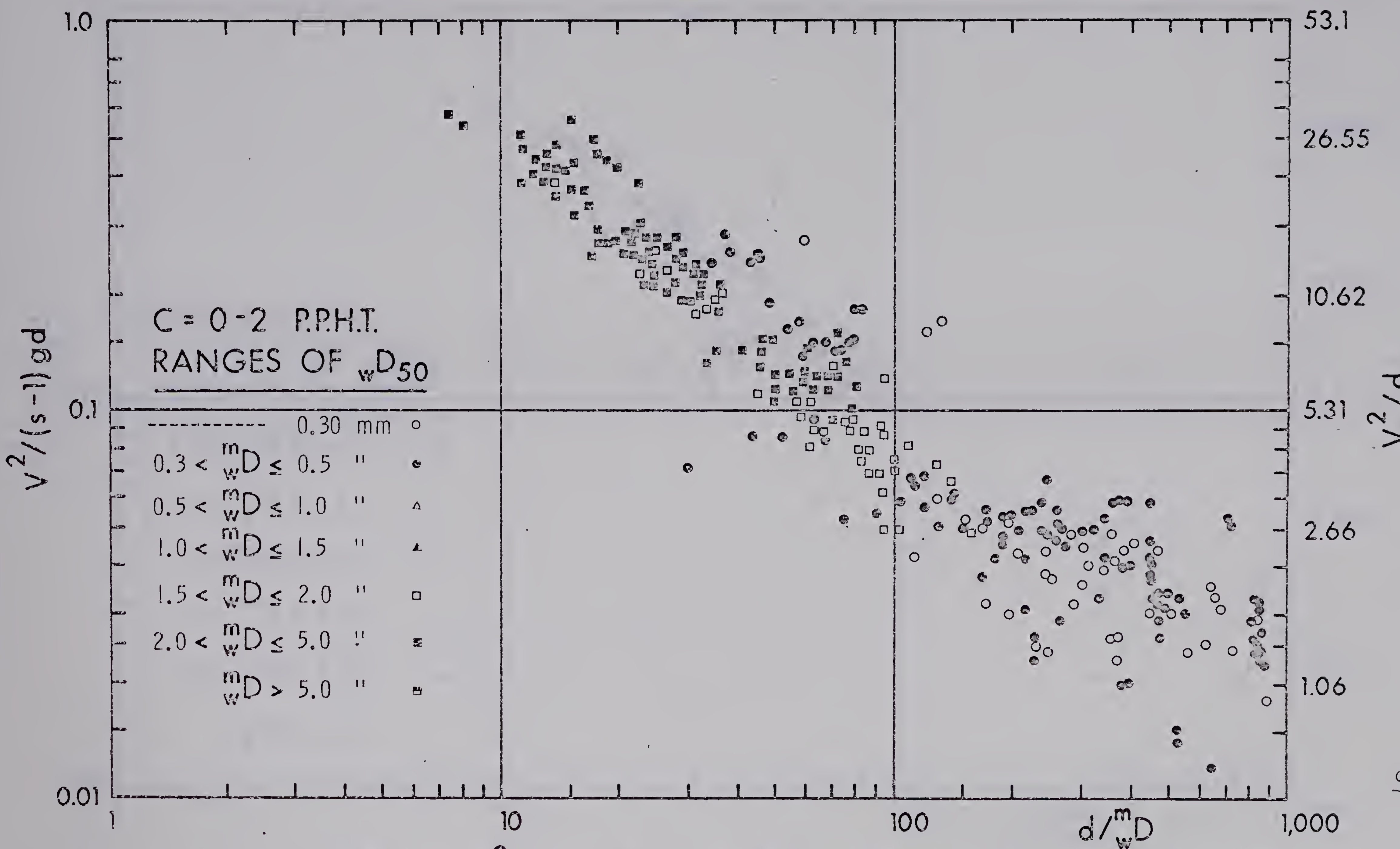



FIG. 4-4 (a) PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_wD$ SHOWING THE EFFECT OF ${}^m_wD$

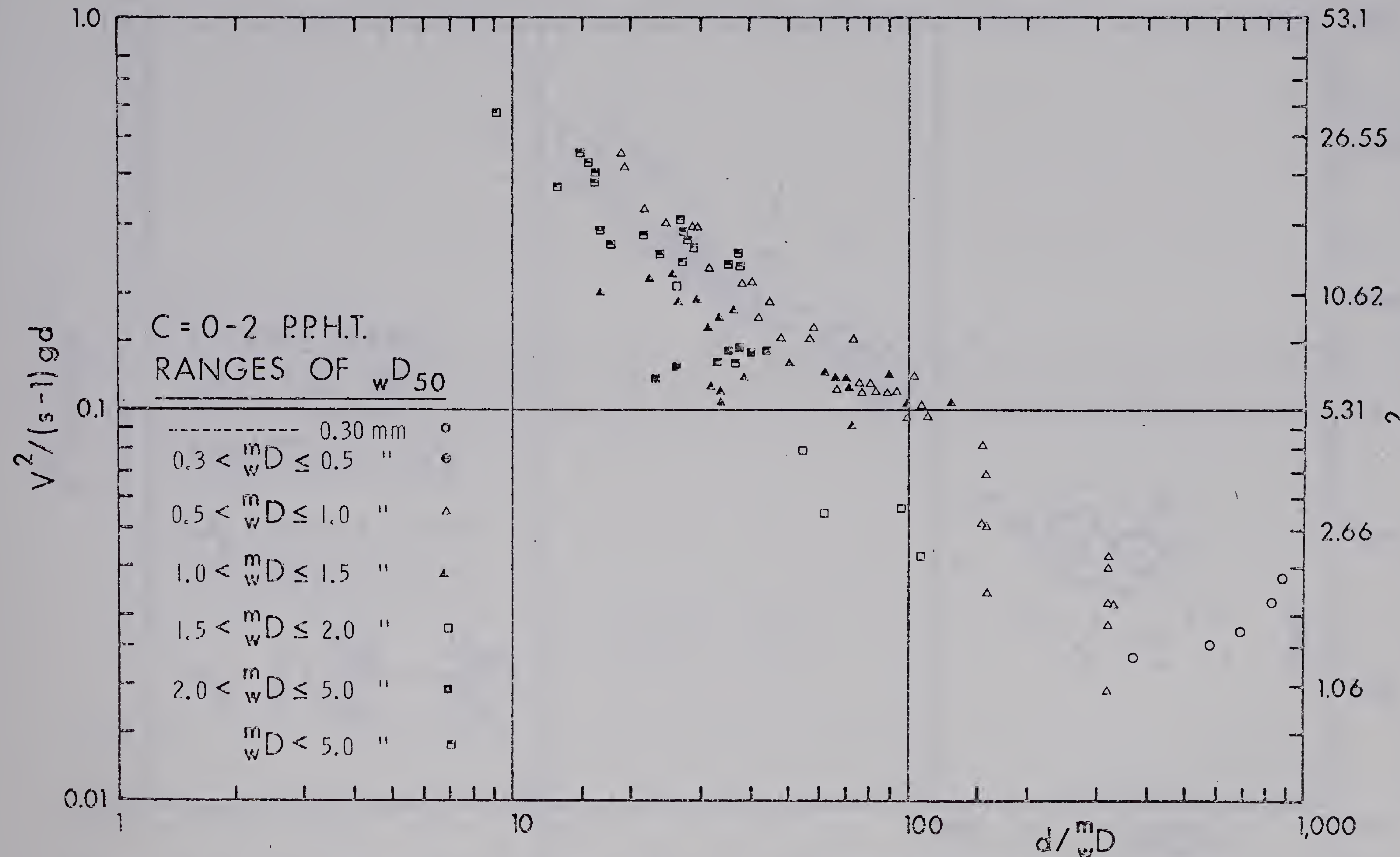



FIG. 4-4 (b) PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_wD$ SHOWING THE EFFECT OF ${}^m_wD$

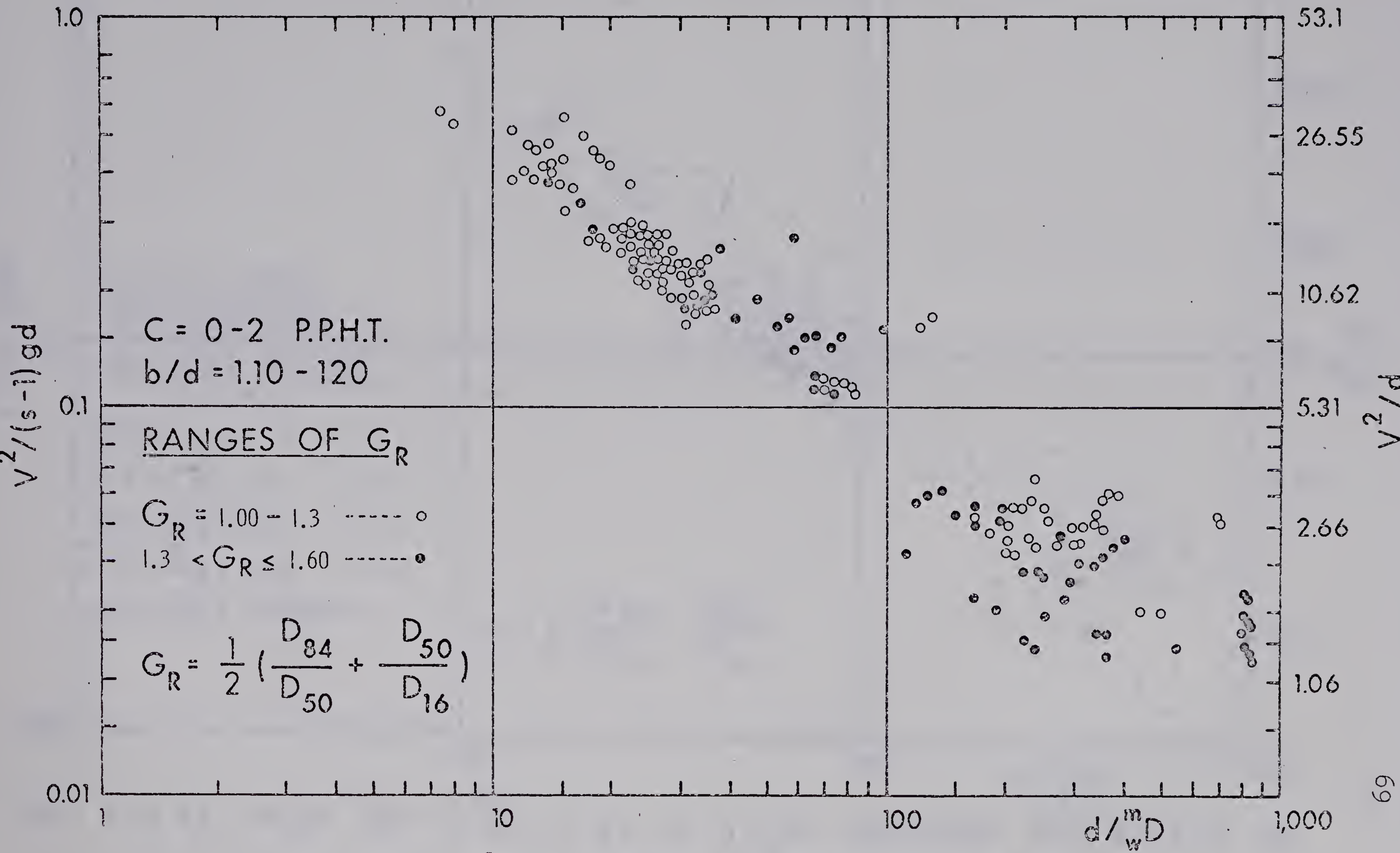



FIG. 4-5 (a) PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$ SHOWING THE EFFECT OF $G_R$

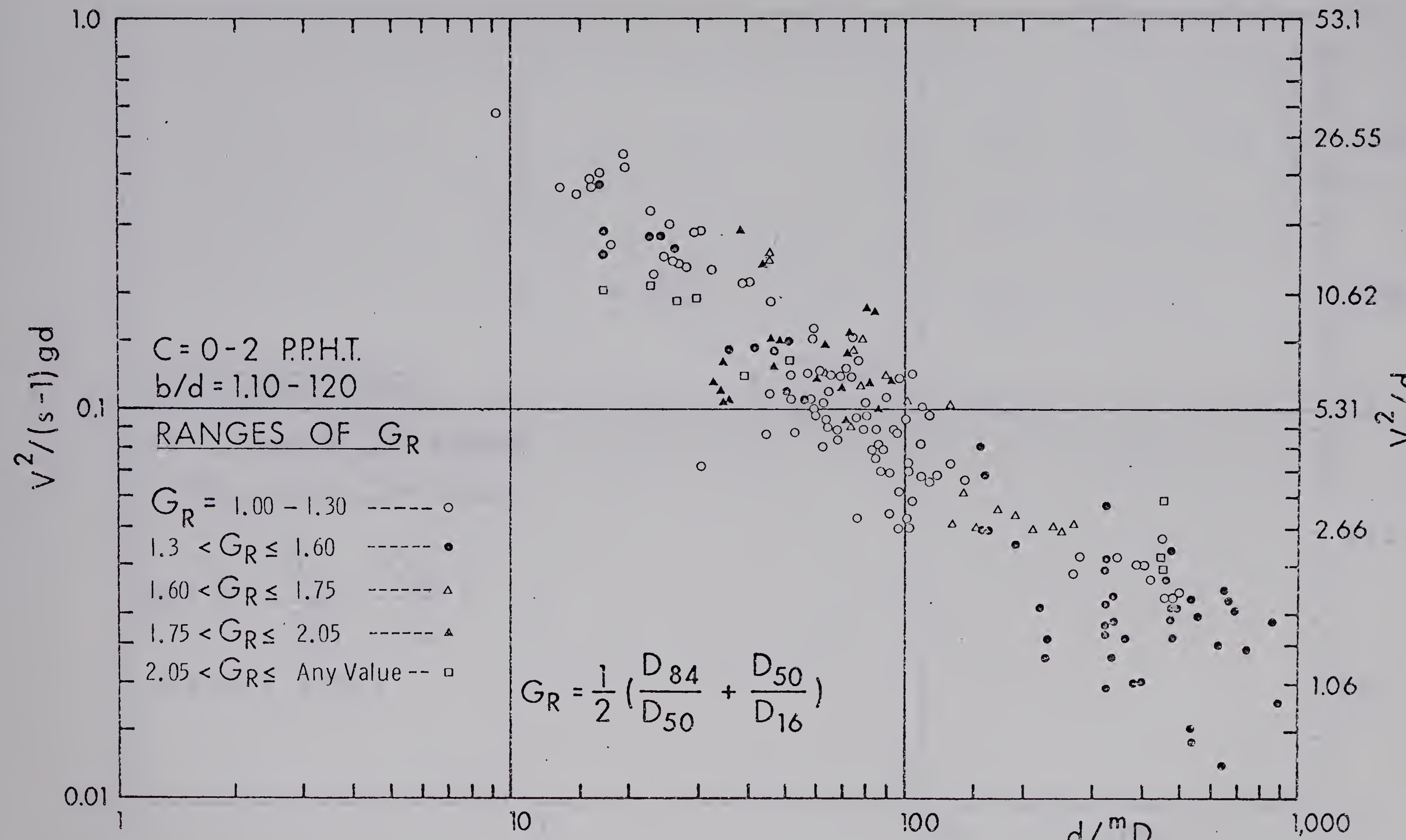
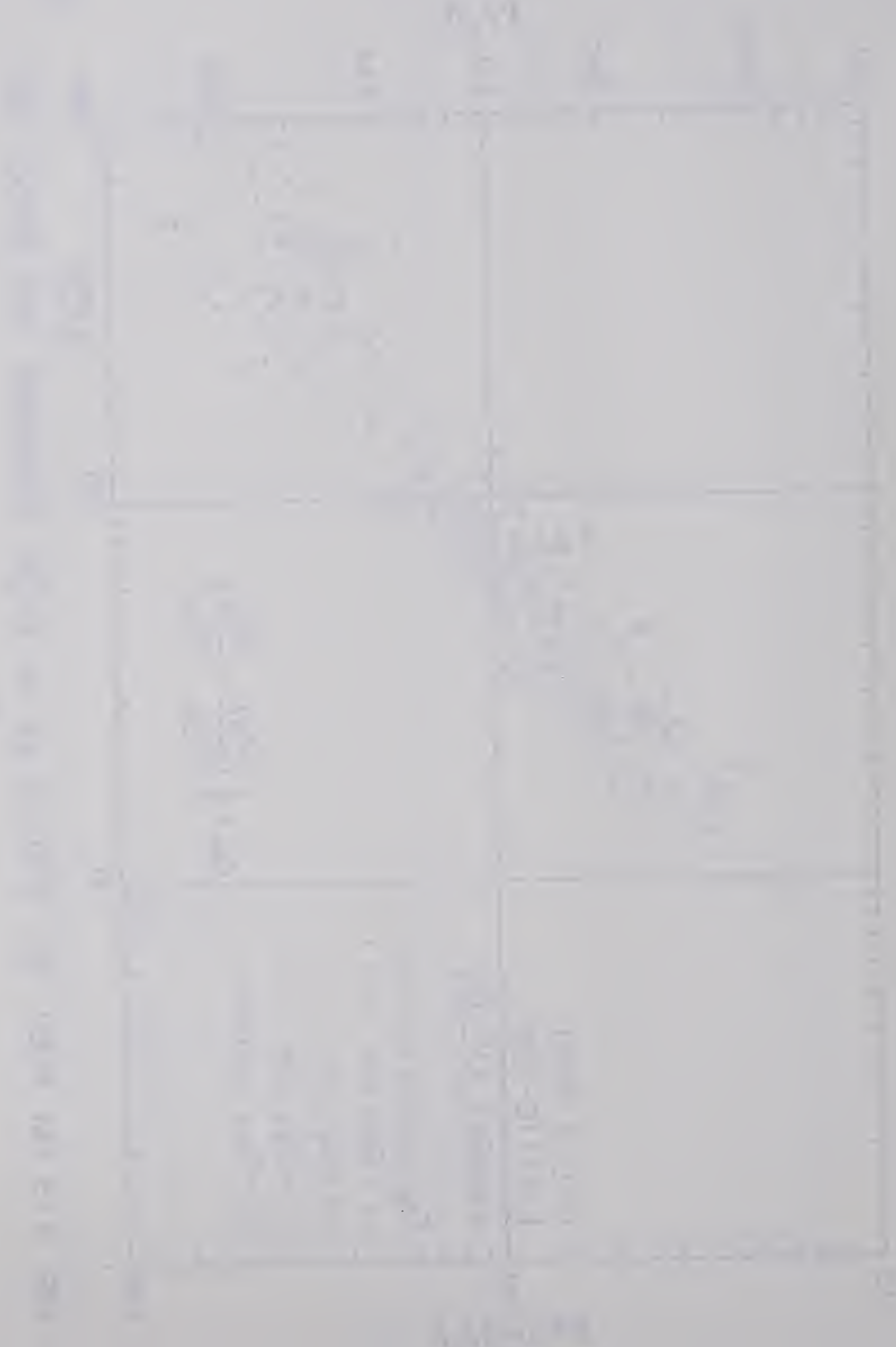



FIG. 4-5 (b) PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_w D$ SHOWING THE EFFECT OF $G_R$



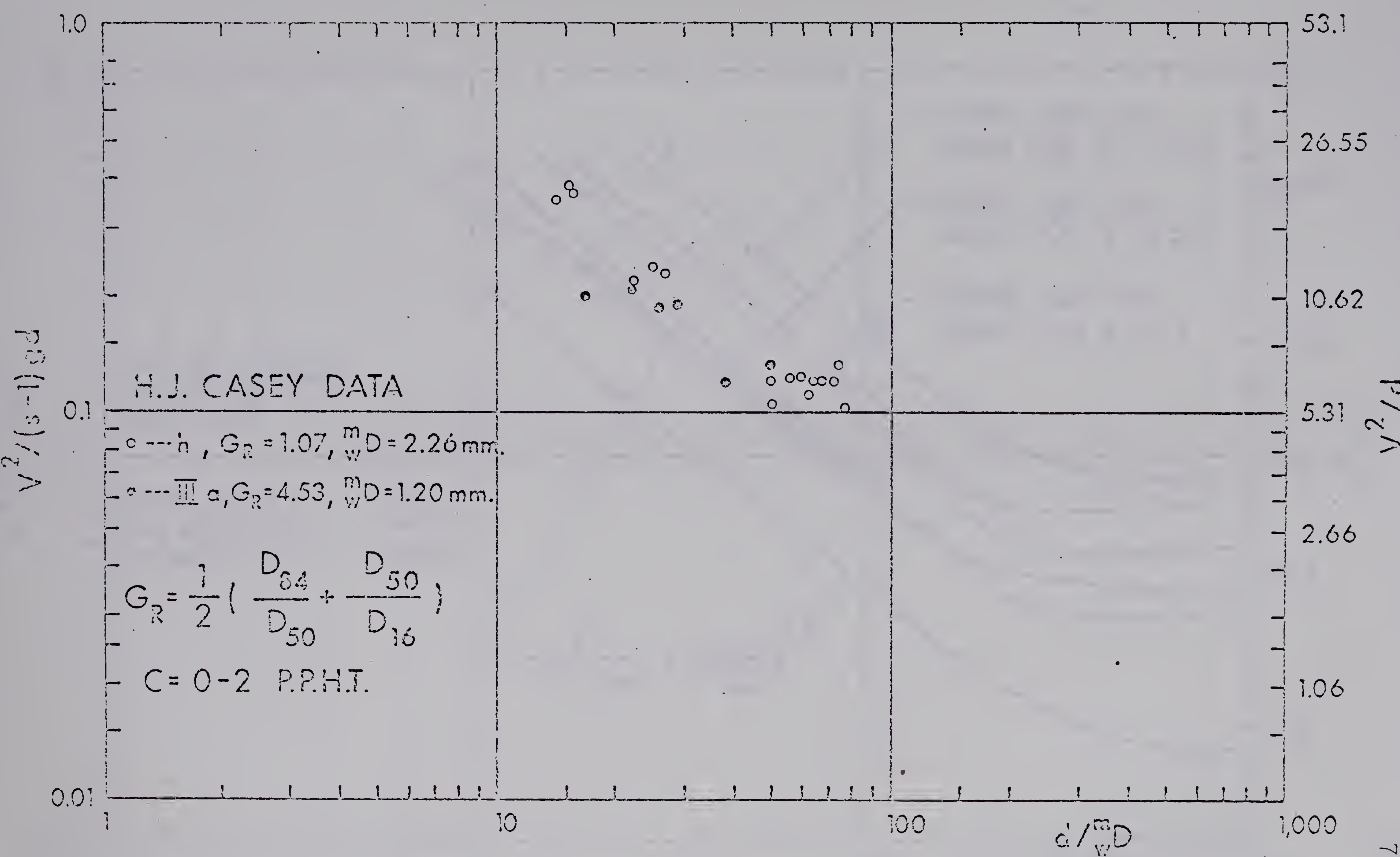



FIG. 4-5 (c) PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ FOR H.J. CASEY DATA SHOWING THE EFFECT OF $G_R$

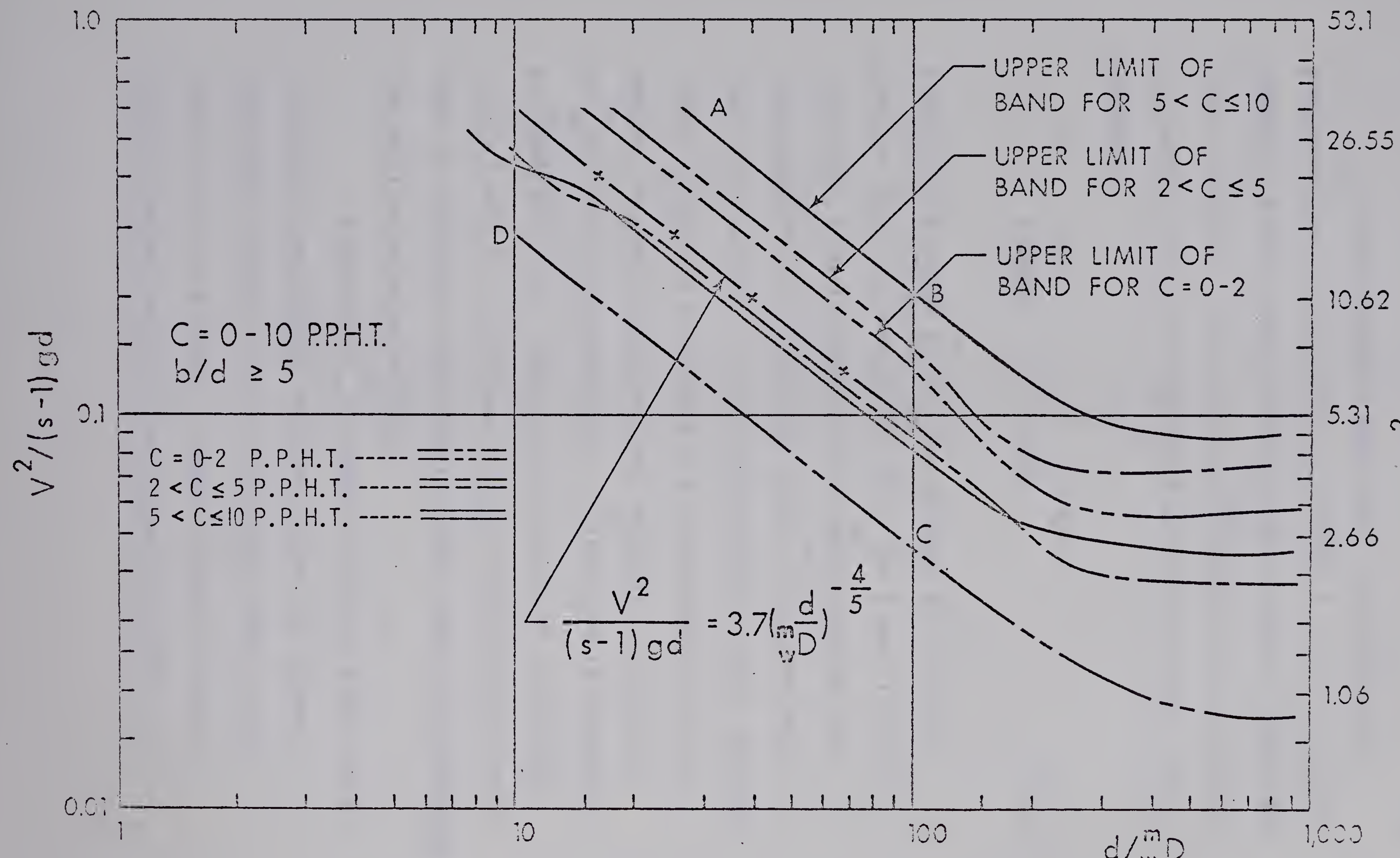



FIG. 4-6 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ FOR C = 0-10, b/d ≥ 5

The composite band ABCD in FIGURE 4.6 encloses the plotted data of FIGURE 4.1 to 4.3 where charge C varies from 0.0 to 10.00 P.P.H.T. This band has a slope of -4/5 in the $d/{}_{w}^{m}D$ range of 10 to 100. The central line of this band appears to follow the relation

$$\frac{V^2}{(s-1)gd} = 3.7 \left(\frac{d}{{}_{w}^{m}D}\right)^{-4/5} \qquad (4.2.1)$$

within this range of $d/{}_{w}^{m}D$. Beyond $d/{}_{w}^{m}D$ value greater than approximately 400, the lines limiting the bands tend to become horizontal showing the independence of $V^2/(s-1)gd$ on $d/{}_{w}^{m}D$ in this zone. From observations in the Indo-Gangetic canal systems where $\rho_s/\rho_f$ and X factors are practically fixed by nature, regime theory workers explain that beyond $d/{}_{w}^{m}D > 400$ (approximately), $V^2/(s-1)gd$ is dependent on $\sqrt[3]{\nu g(s-1)}\, D/\nu$. This is also noticed in FIGURES 4.4 (a) and 4.4 (b) where points representing larger size of materials fall mostly above those representing the smaller size materials.

Between $d/{}_{w}^{m}D$ values of 100 to 400, there is curious transition between those two phases described earlier. This transition seems to be parallel to that found in conventional friction factor diagram and in this transition zone

$V^2/(s-1)gd$ appears to depend on $d/{}_{w}^{m}D$, C, $\sqrt[3]{g(s-1)}\,D/\nu$ and may be on "X" factors too. Sufficient flume-data covering $d/{}_{w}^{m}D$ range of 1 to 10 were not available. As a result, the nature of relation between the relevant parameters in this zone could not be reliably studied. Moreover, when $V^2/(s-1)gd$ exceeds about 0.6 the flow becomes supercritical. Available bed-load transport-data from flume experiments with low charge ($C \angle 10$ P.P.H.T.) and covering this phase (supercritical) of flow are insufficient. But from the limited amount of transport data plotted in FIGURE 4.7 and from the fair number of "initiation" data collected by Neill and others and plotted in FIGURE 4.8 some speculations may be made. These "initiation" data cover a $V^2/(s-1)gd$ range of 0.6 to 2.0 and $d/{}_{w}^{m}D$ range of 2 to 10. When FIGURE 4.6 is superimposed on FIGURES 4.7 and 4.8 it appears that the relation between $V^2/(s-1)gd$ and $d/{}_{w}^{m}D$ in the $d/{}_{w}^{m}D$ range of 2 to 10 follow closely their relation in the $d/{}_{w}^{m}D$ range of 10 to 100.

The three bands in FIGURE 4.6 each representing one of the three ranges of C as noted earlier show to a certain extent that as C increases the band as a whole moves upward indicating a slightly higher value of $V^2/(s-1)gd$ for same $d/{}_{w}^{m}D$ with an increase in C. This gives the indication that the scatter of plotted points within the band itself

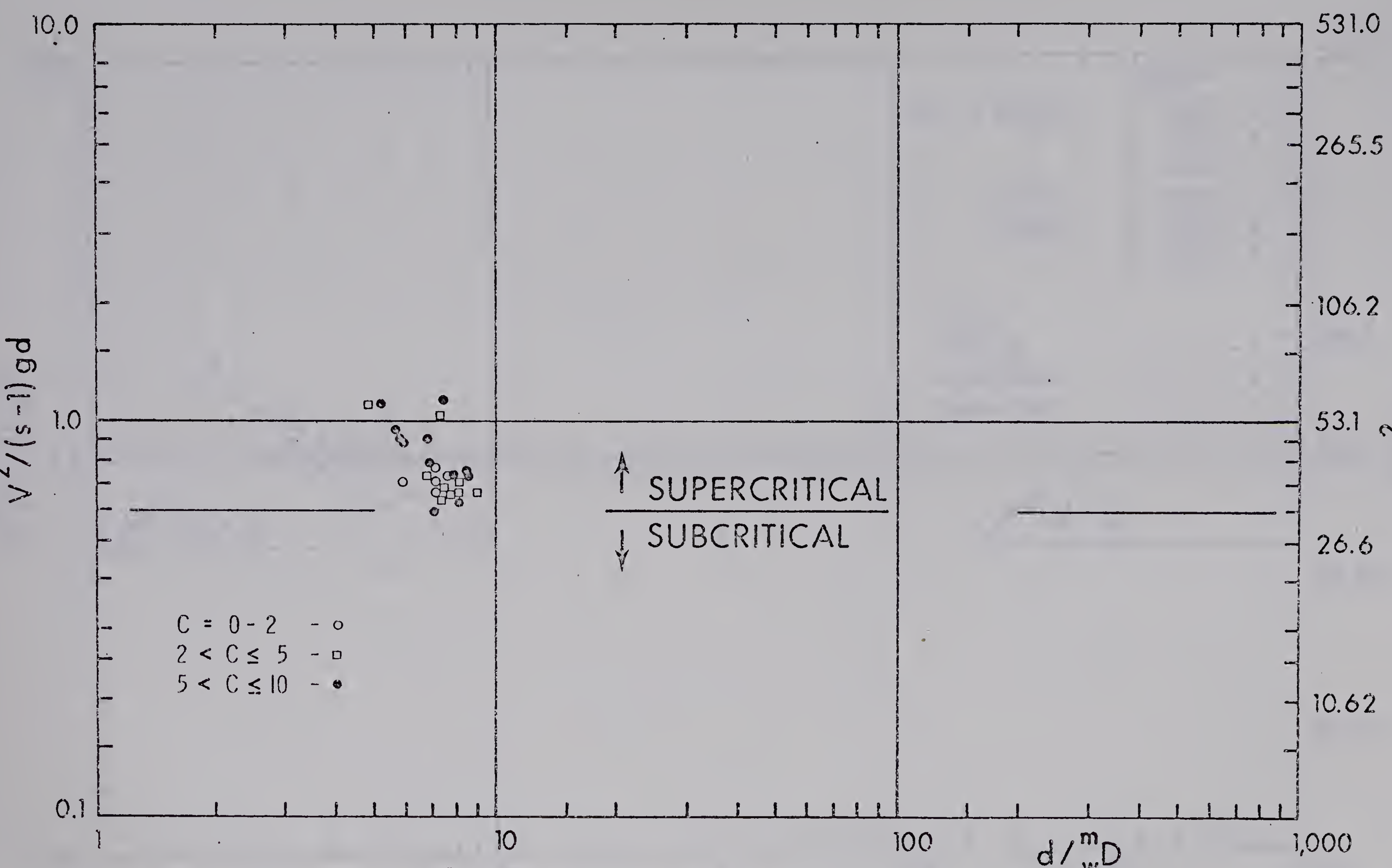



FIG. 4-7 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_wD$ FOR FLUME-TRANSPORT DATA WITH SUPERCRITICAL FLOW

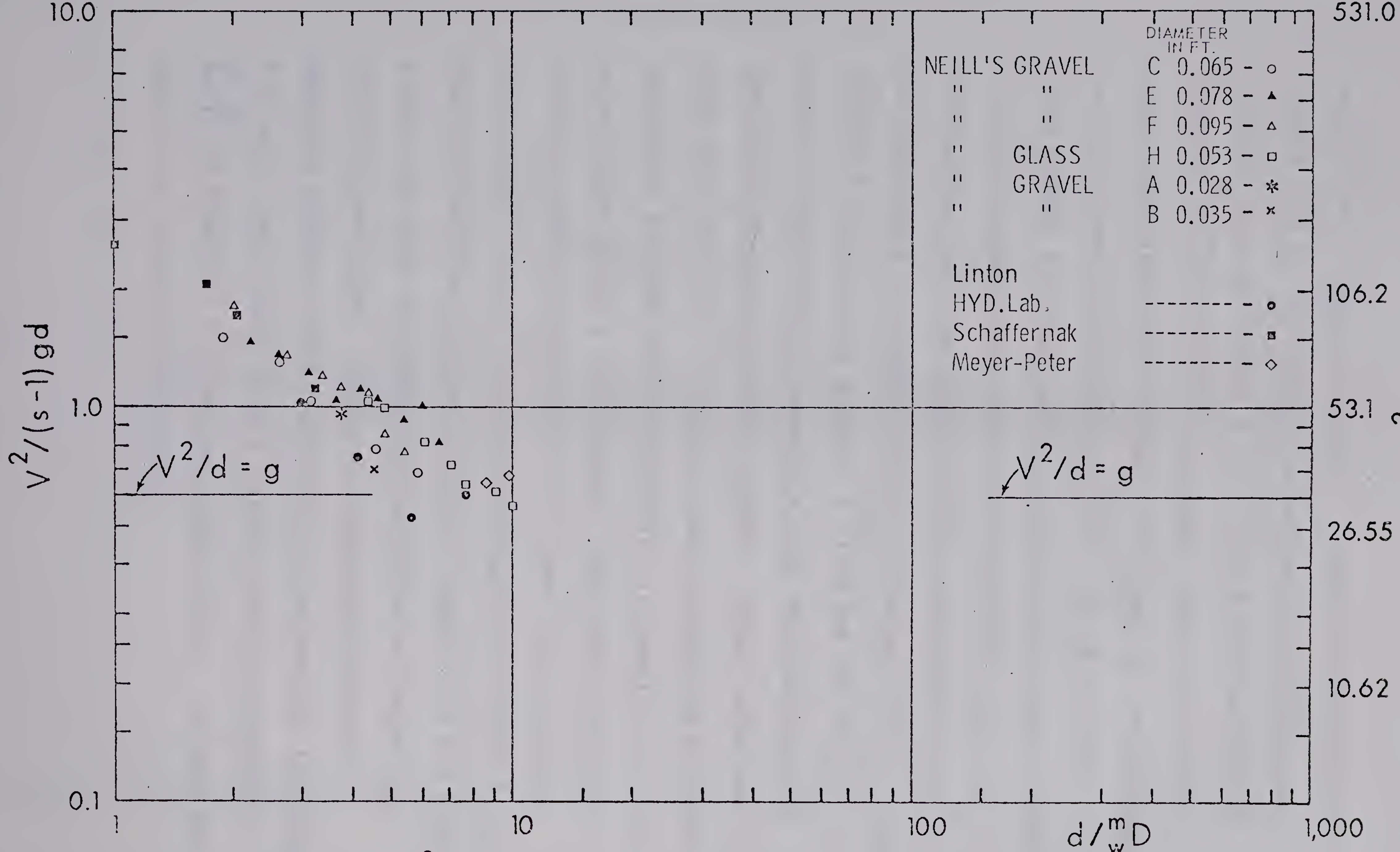



FIG. 4-8 PLOT OF $V^2/(s-1)gd$ vs. $d/^m_wD$ FOR INITIATION DATA WITH SUPERCRITICAL FLOW.

may be due to the variation in C within the range of 0-10 P.P.H.T. To verify the effect of C within the fitting band of FIGURE 4.6, $V^2/(s-1)gd$ was plotted against $d/\,{}^{m}_{w}D$ in FIGURE 4.9 where the plotted data were split into three ranges of C that is C=0.01-0.2, C=1.8-2.0 and C=9.0-9.99 P.P.H.T. It is evident from FIGURE 4.9 that points representing higher values of C fall above those representing lower values of C indicating that the scatter within the band is due to the variation in charge within its range of 0-10 P.P.H.T. FIGURE 4.9 (a) shows a plot $V^2/(s-1)gd$ Vs. $d/\,{}^{m}_{w}D$ for data on light weight materials with various specific gravities mentioned in the figure. These experiments were done by U.S.W.E.S. to examine the suitability of these materials for use as bed-materials in models. In the same figure Neill's "initiation" data with cellulose acetate (specific gravity = 1.31) are also plotted. When FIGURE 4.9 (a) is studied along with FIGURE 4.6 it appears that the plotted points in figure 4.9 (a) fall within the band of Figure 4.6 in spite of their low specific gravities. Also, no systematic effect of specific gravity can be noticed on the scatter in FIGURE 4.9 (a). This leads to the belief that the parameter $\rho_s/\rho_f$ in Equation 4.1 can be taken care of, if data are plotted in terms of $V^2/(s-1)gd$.

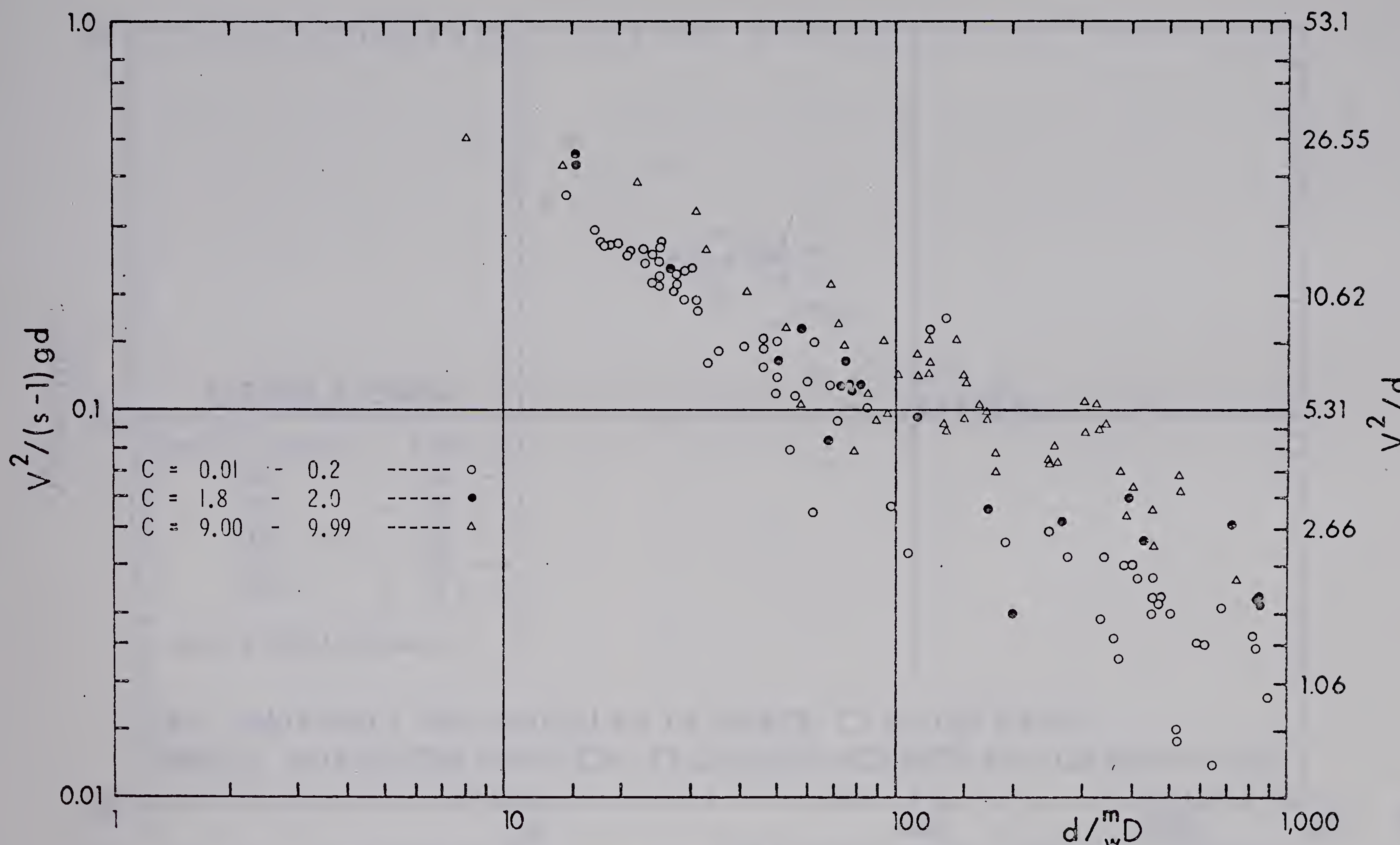



FIG. 4-9 PLOT OF $V^2/(s-1)$ gd vs. $d/{}^m_wD$ SHOWING THE EFFECT OF CHARGE, C

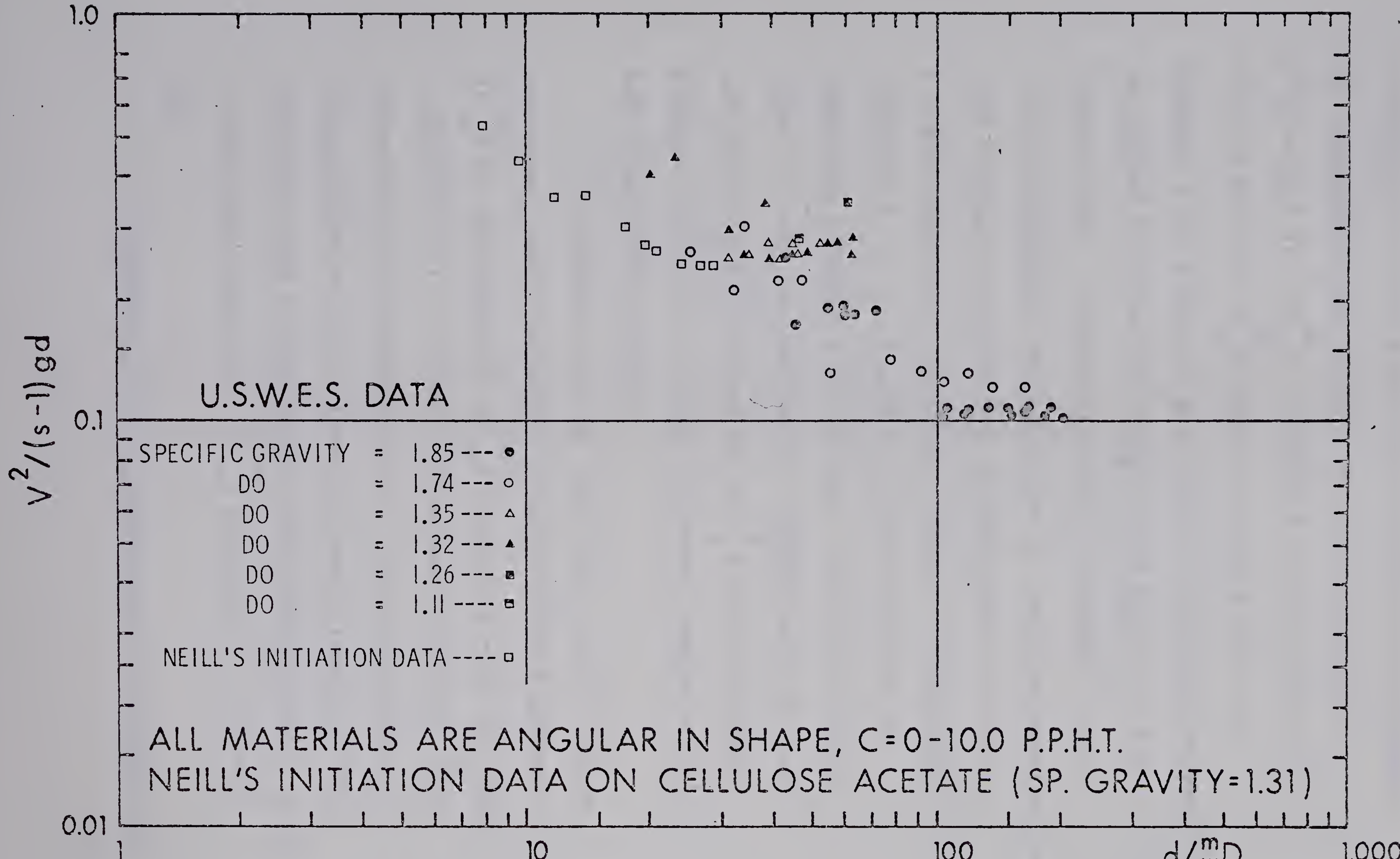



FIG. 4-9 (a) . PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ FOR LIGHT WEIGHT MATERIALS

FIGURES 4.10 to 4.13 are the results of an attempt to investigate the effect of b/d on the plot of $V^2/(s-1)gd$ Vs. $d/{}_{w}^{m}D$. FIGURE 4.10 is a plot of $V^2/(s-1)gd$ Vs. $d/{}_{w}^{m}D$ for C = 0-2 P.P.H.T. and FIGURES 4.11 and 4.12 are plots of same parameters as FIGURE 4.10 but for $2 < C \leq 5$ and $5 < C \leq 10$ P.P.H.T. respectively. Points plotted in FIGURES 4.10 to 4.12 are grouped, irrespective of their authors, as per various ranges of b/d values as mentioned in article 4.1 and also noted in these figures. These plots (FIGURES 4.10, 4.11 and 4.12) are obtained by combining FIGURES A-18 to A-21, A-22 to A-25 and A-26a to A-29 respectively. FIGURES A-18 to A-29 are plots of $V^2/(s-1)gd$ Vs. $d/{}_{w}^{m}D$ for individual authors' data and for the different ranges of b/d and C as noted earlier.

FIGURES 4.10 to 4.12 show, on the whole, the same kind of relation between $V^2/(s-1)gd$ and $d/{}_{w}^{m}D$ in the range of $d/{}_{w}^{m}D$ between 10-100 as found in FIGURES 4.1 to 4.3 and discussed earlier. The intermixing in the position of the plotted points irrespective of their four different ranges of b/d indicates that b/d does not have any systematic effect on the plot within the $d/{}_{w}^{m}D$ range of 10 to about 500.

FIGURE 4.13 is a counterpart of FIGURE 4.6

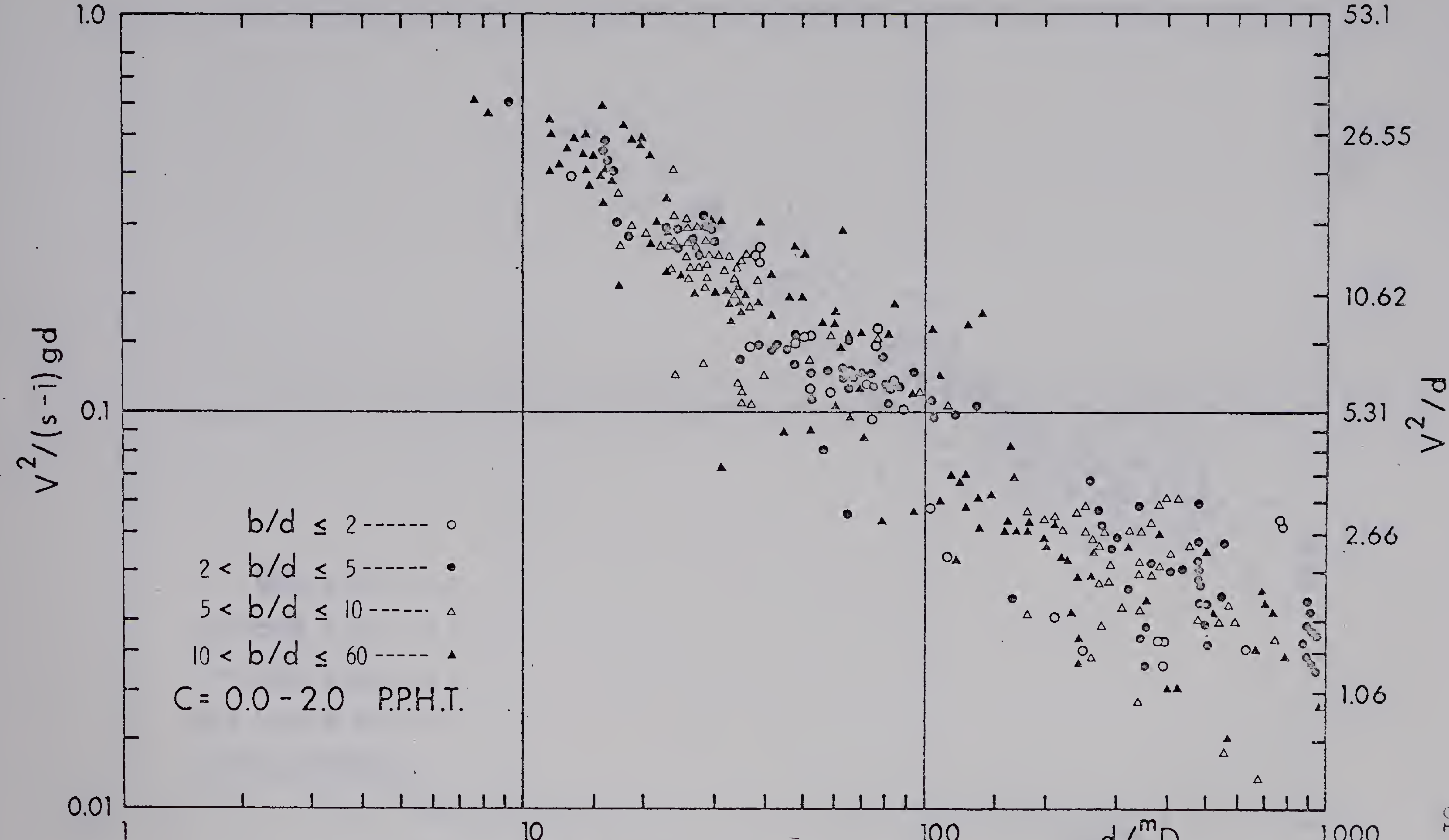



FIG. 4-10 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_w D$ SHOWING THE EFFECT OF b/d

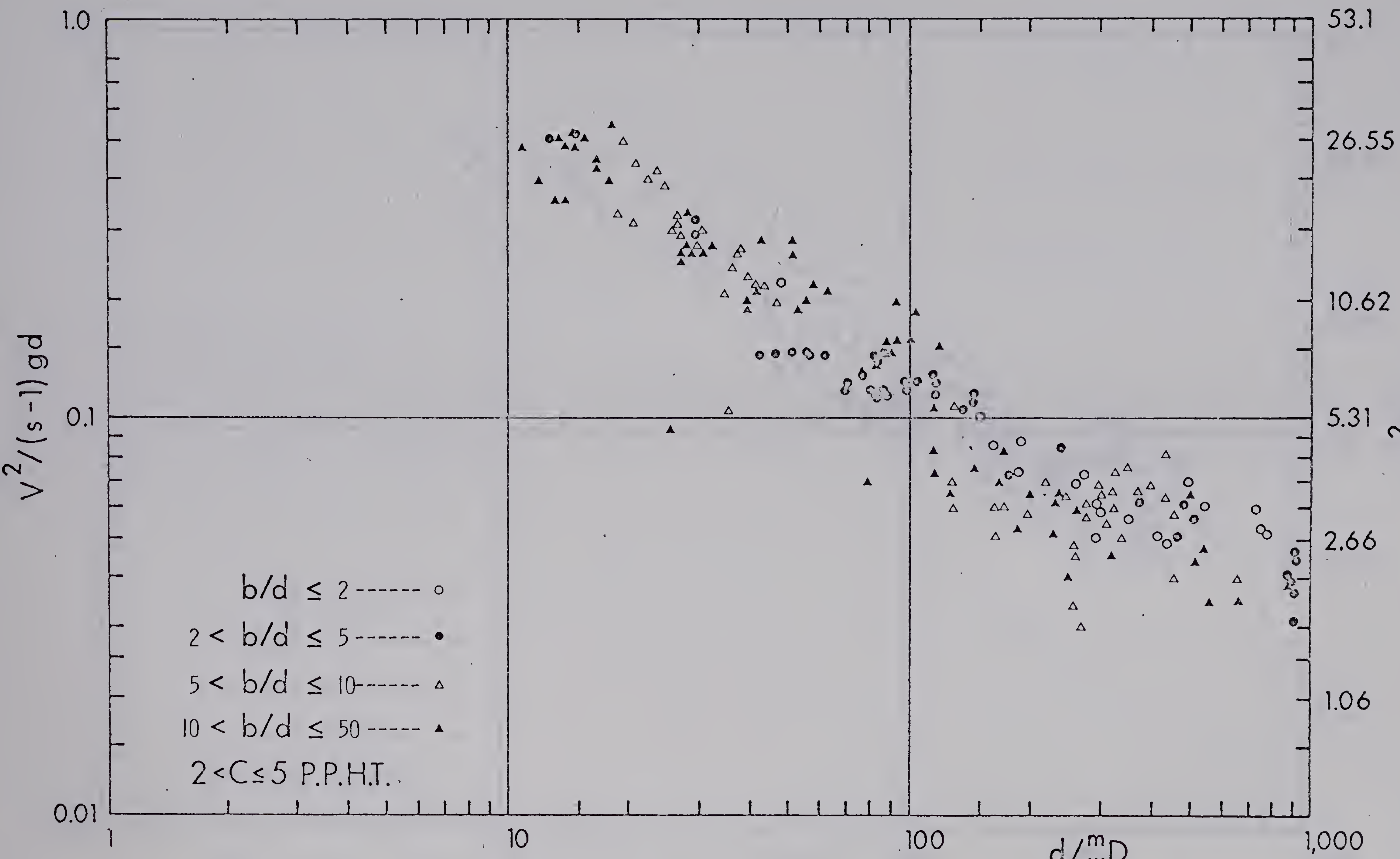



FIG. 4-11 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$ SHOWING THE EFFECT OF $b/d$

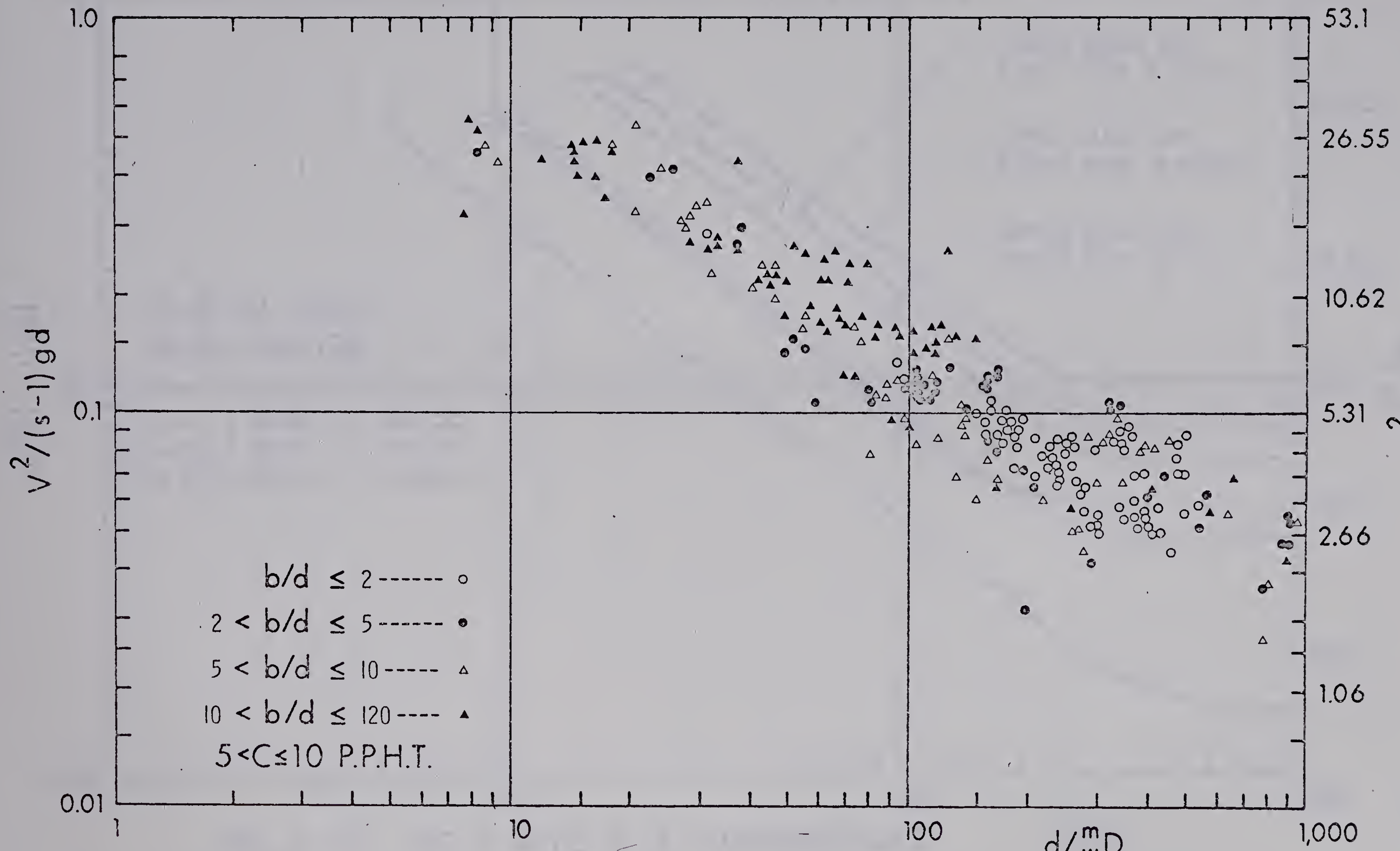



FIG. 4-12 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$ SHOWING THE EFFECT OF b/d

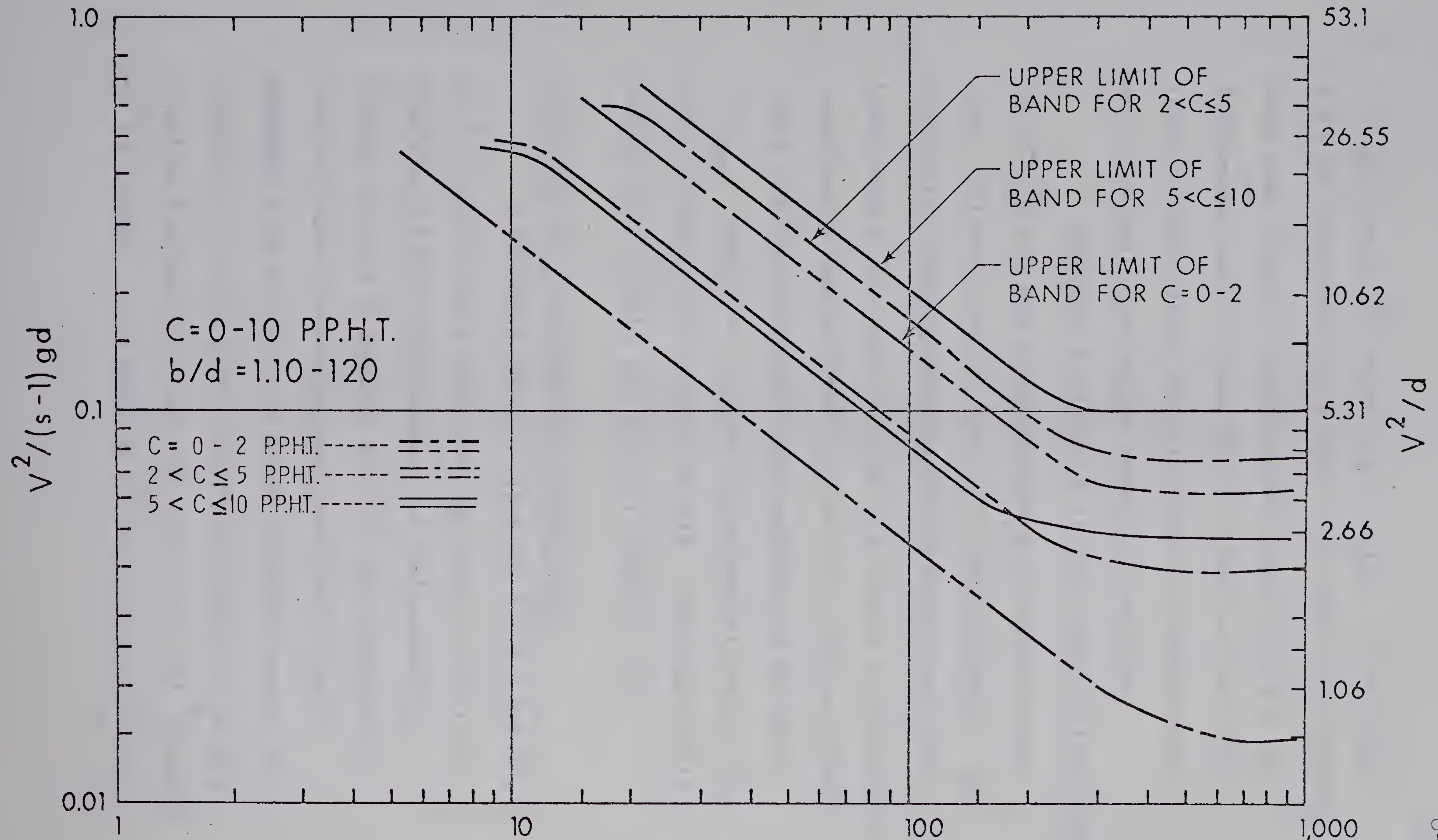



FIG. 4-13 FIG. 4-10 TO 4-12 SUPERIMPOSED. $d/{}^{m}_{w}D$

with b/d range of about 1.10 to 120. When FIGURE 4.13 is compared with FIGURE 4.6, where the plotted data come from the experiments where b/d $\geqslant 5$, no difference can be found between the two and this leads to the belief that the plot is independent of b/d within the ranges mentioned earlier.

FIGURES 4.14 and 4.15 are plots $V^2/(s-1)gd$ Vs. $d/{}_w^mD$ for the data collected by Bhattacharya (Ref. 33) and Qureshi (Ref. 34) respectively. The b/d ratio in Bhattacharya's experiments were all less than 5 and the range of b/d values in Qureshi's experiments varied from 1.95 to 7.3. In both the cases the bed-condition was reported to be that of $F_{bo}$ - condition in most experimental runs. In spite of their low values of b/d, the points fall fairly well within the band of FIGURE 4.13.

## 4.3 TREATMENT OF "INIATION OF MOTION" DATA

FIGURE 4.16 is a plot of $V^2/(s-1)gd$ Vs. $d/{}_w^mD$ for the data collected by Neill (1966) to study the first displacement of bed-materials. FIGURE 4.17 is a similar plot of the comparable data of other investigators provided by Neill. FIGURES 4.16 and 4.17 plotted together result in FIGURE 4.18 which shows close accordance with the results discussed in Article 4.2 in the $d/{}_w^mD$ range of 10 to 100. If FIGURE 4.18 is superimposed on

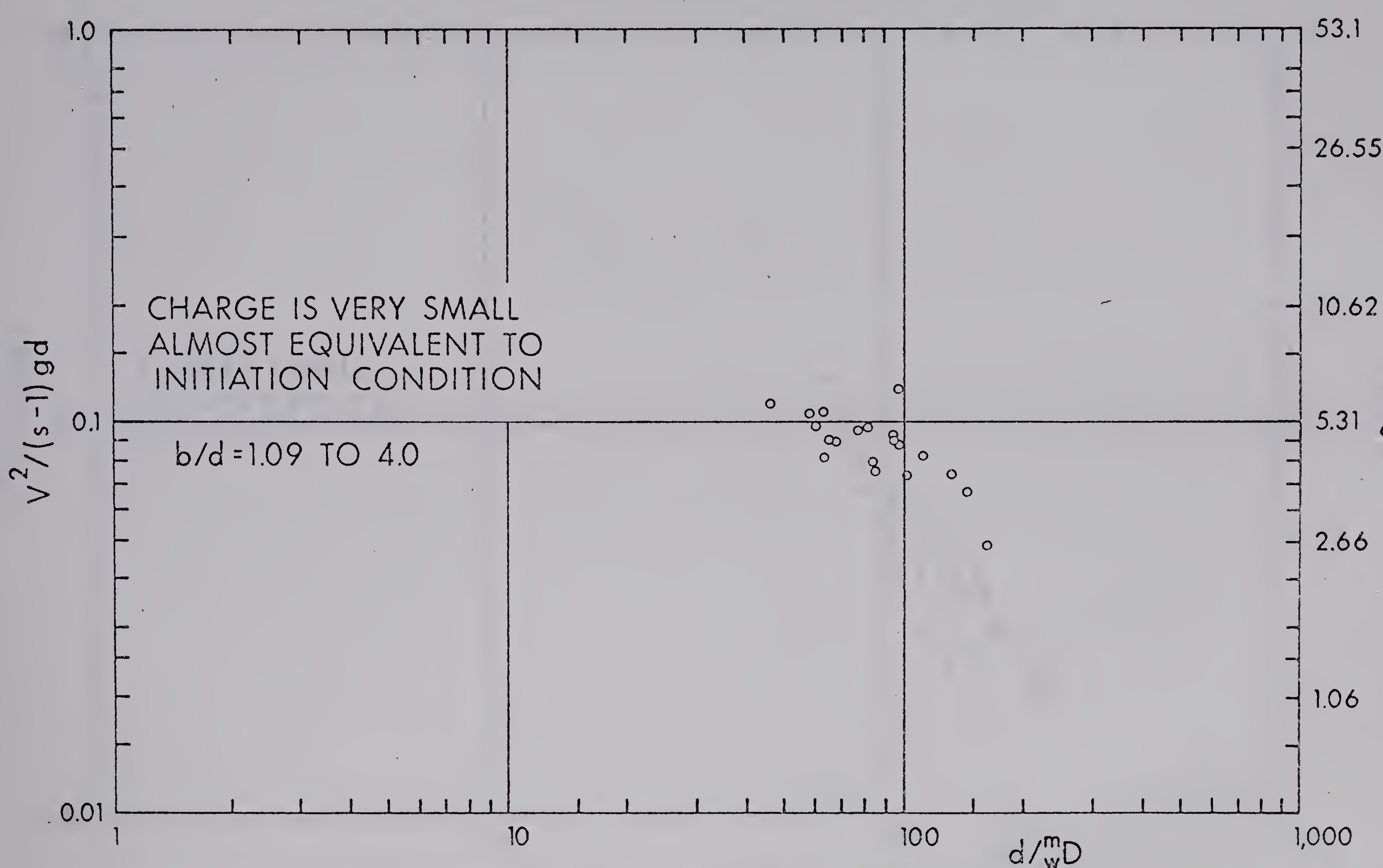



FIG. 4-14 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ SHOWING EFFECT OF b/d
BATTACHARYA'S DATA

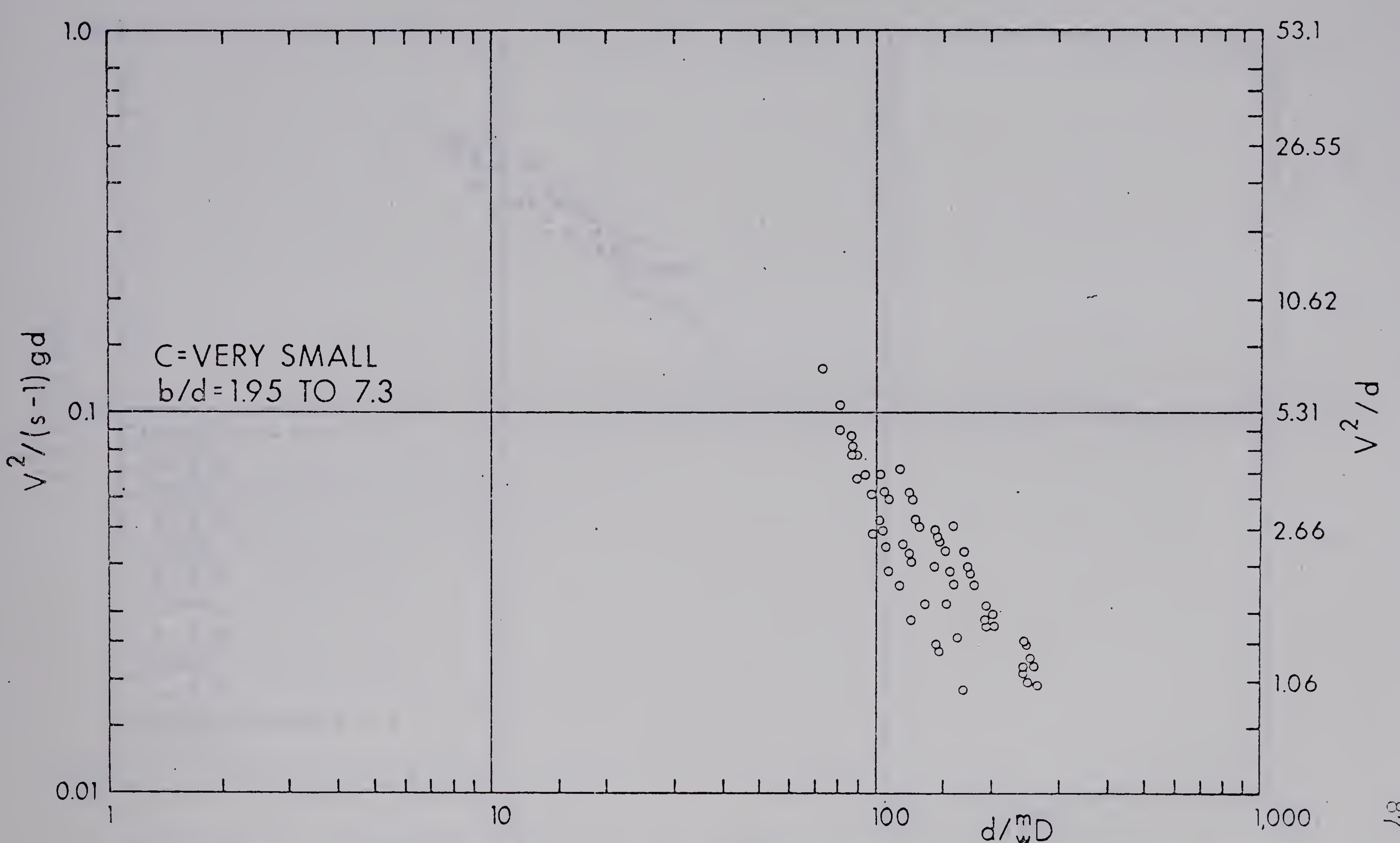



FIG. 4-15 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ SHOWING EFFECT OF b/d QURESHI'S DATA

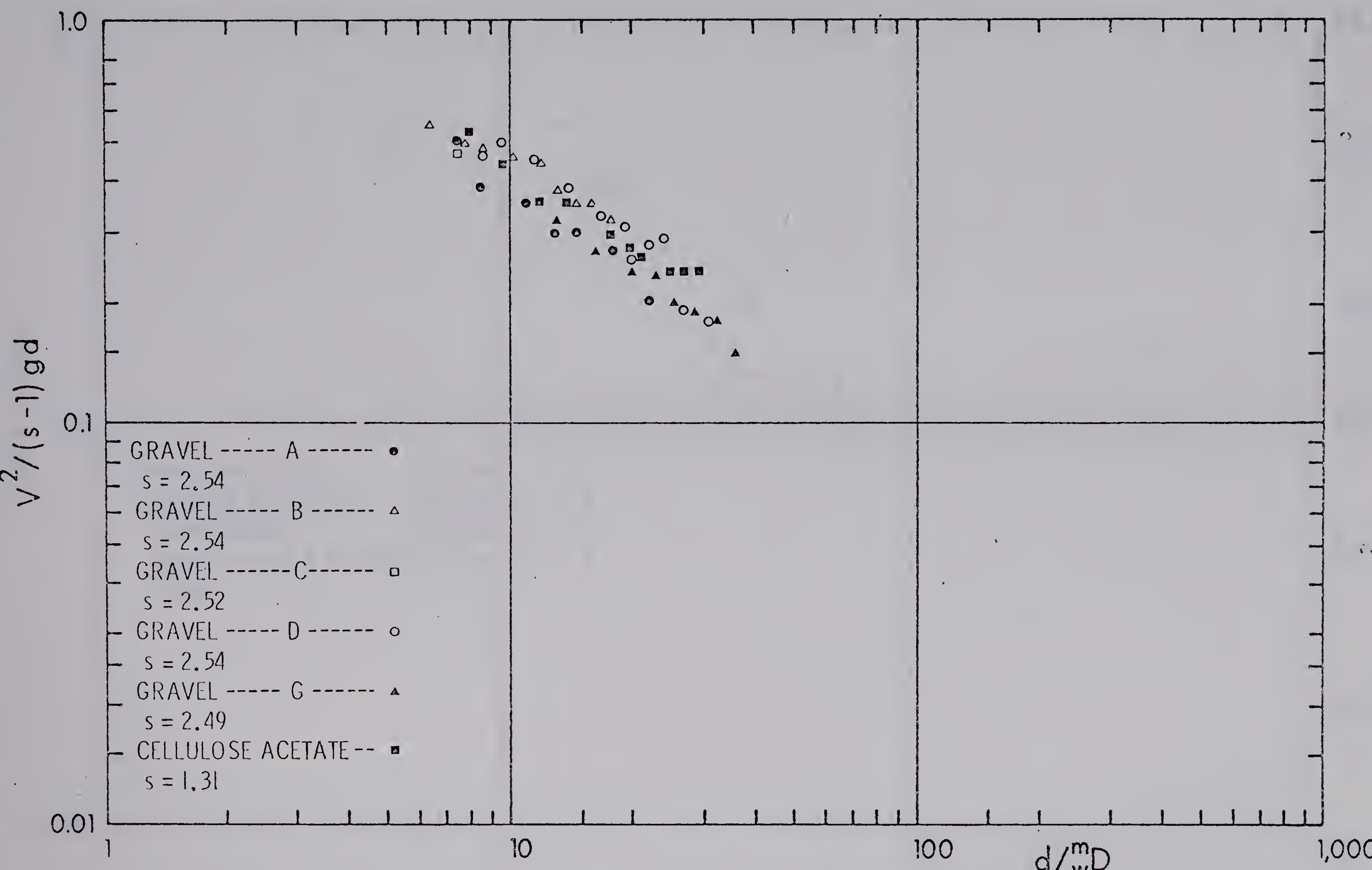



FIG. 4-16 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^{m}_{w}D$ FOR NEILL'S "INITIATION OF MOTION" DATA

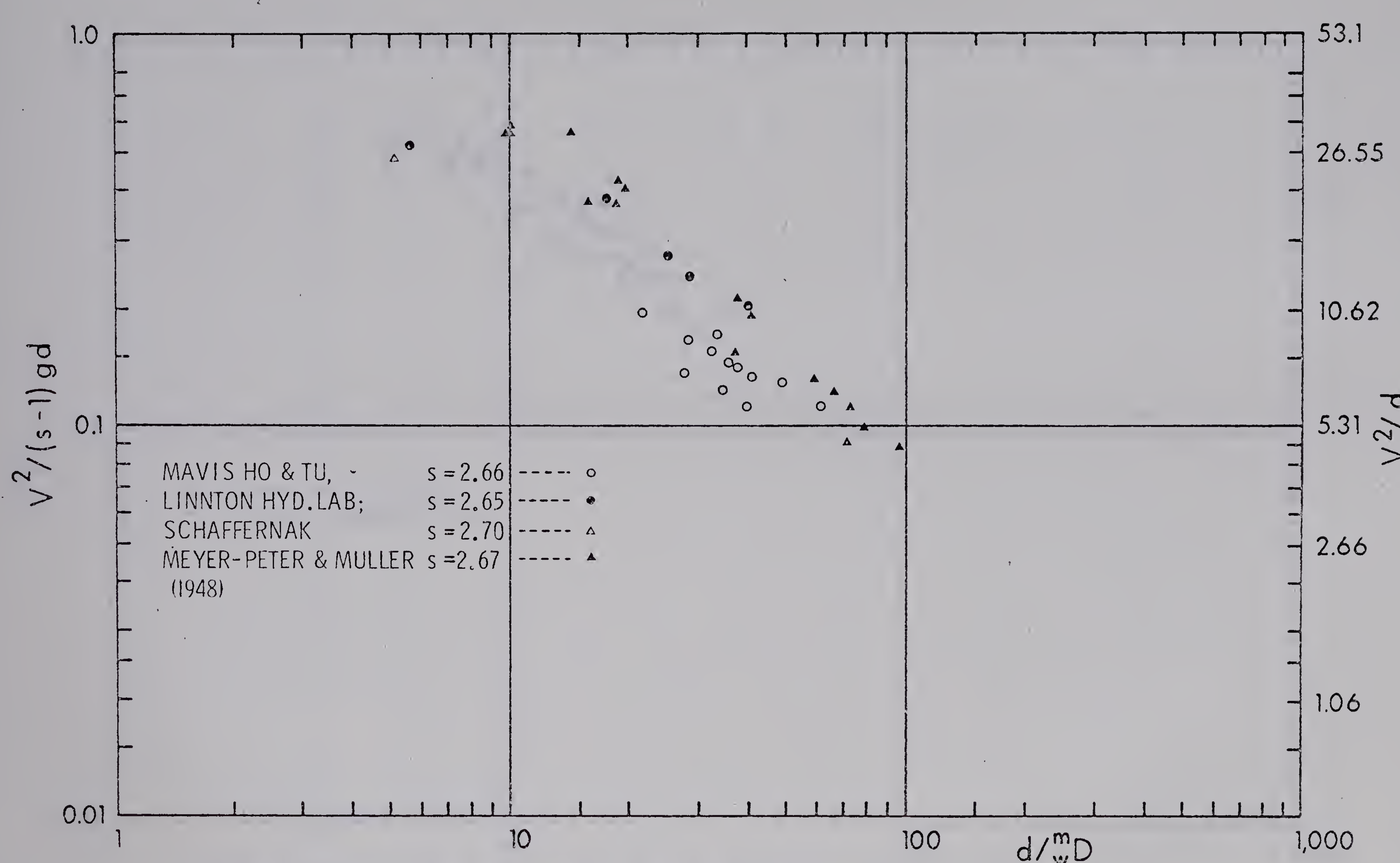



FIG. 4-17 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$ FOR OTHER LABORATORY DATA ON "INITIATION OF MOTION" (REPORTED BY NEILL)

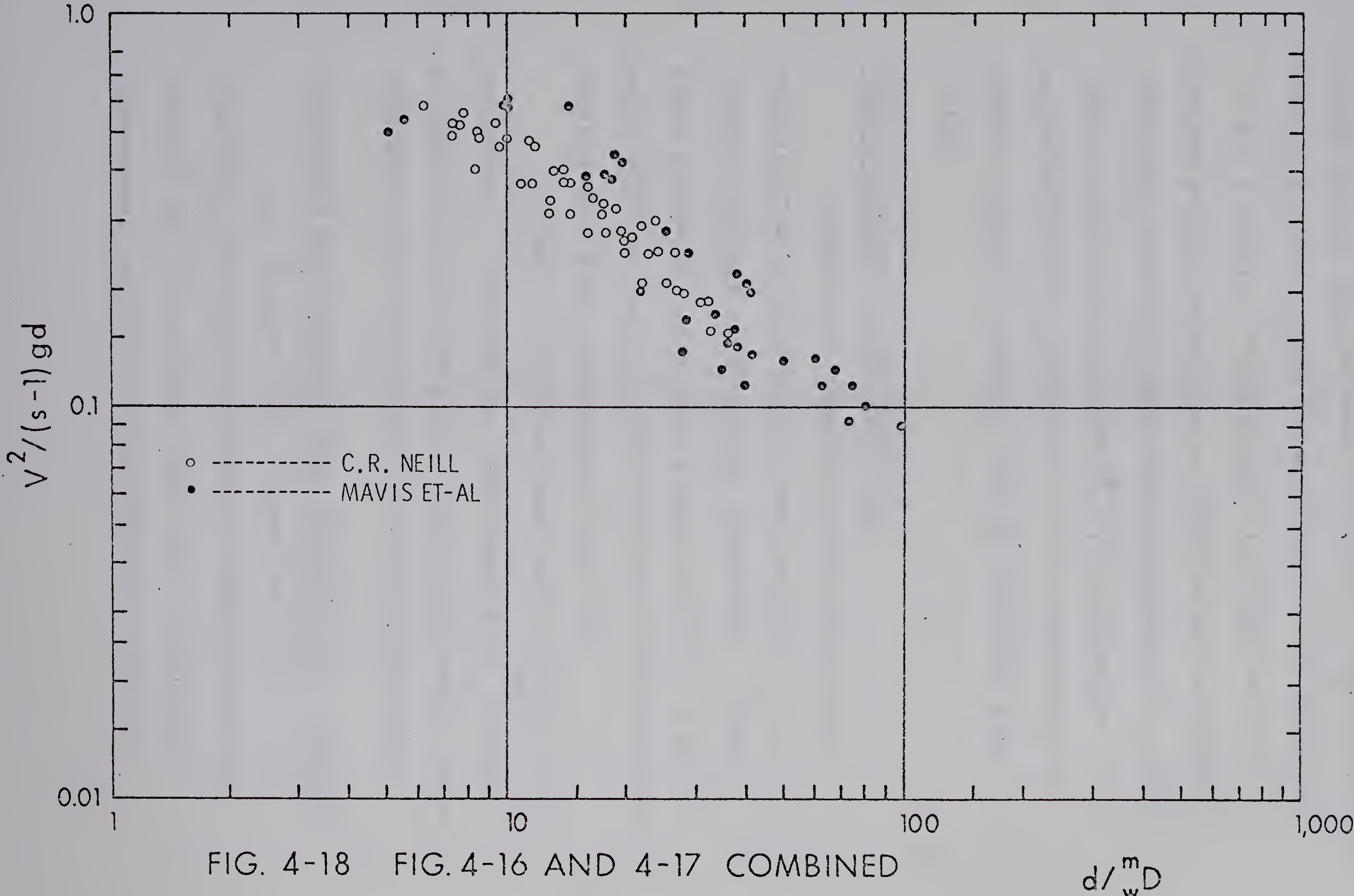



FIG. 4-18 FIG. 4-16 AND 4-17 COMBINED

FIGURE 4.6, it will be seen that most of the initiation data fall close to the bottom limit of the band for C = 0-2 P.P.H.T. The positions in FIGURE 4.16 of plotted points pertaining to light weight materials (cellulose acetate) whose specific gravity is 1.31 indicate that the parameter $\rho_s / \rho_f$ in Equation 4.1 may be effectively taken care of by considering the buoyant weight of sediment and by replacing g by (s-1)g.

## 4.4 TEST OF ANALYSIS WITH FIELD DATA

Field data observed on the Elbow River described in Article 3.5.10 were available to test the results obtained by analysing flume-data. FIGURE 4.19 shows a plot of these data along with data on gravel-bed irrigation canals in the San Luis Valley (Colorado) collected by Lane and Carlson (Ref. 38).

Table D-1 and D-2 show their observed flow parameters. Although the data cover a $d/{}_{w}D_{m}$ range of about 10 to 60 the plot, within this range, looks consistent with the results of flume experiments.

## 4.5 COMPARISON WITH BED-LOAD DATA ANALYSIS BY J. ROTTNER

J. Rottner (Ref. 6) analysed about 2,500 flume data recorded by different investigators and compiled by J. W. Johnson (Ref. 28). Applying dimensional analysis to the problem he came up

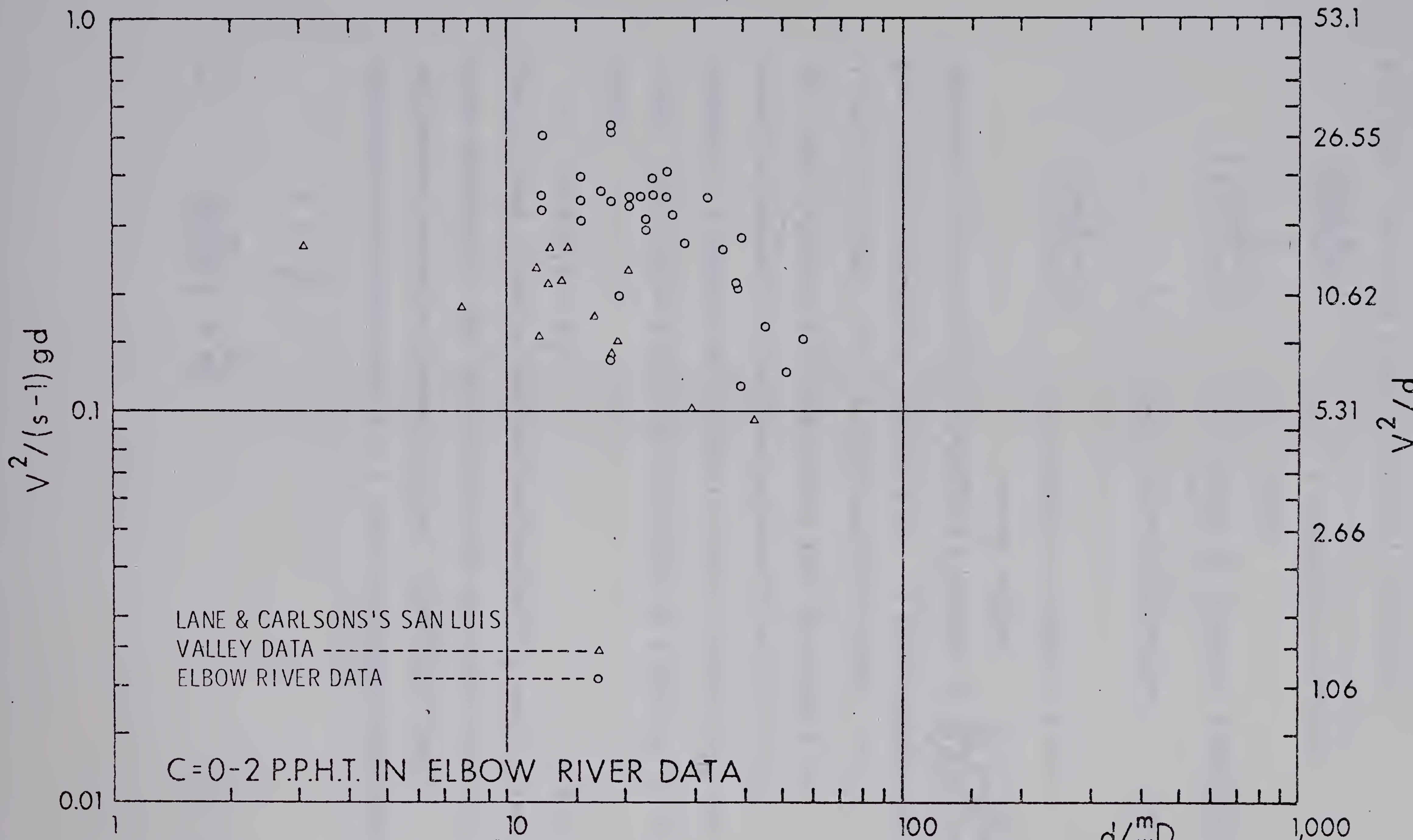



FIG. 4-19 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$ FOR FIELD DATA

with the following non-dimensional parameters

$\frac{V}{\sqrt{gd(s-1)}}$ ----- a densimetric Froude number

$\frac{G}{\rho_s\sqrt{gd^3(s-1)}}$ ----- where G is solid discharge per unit width

$\frac{d}{D}$ ----- as defined before

$\frac{q}{\sqrt{gd^3(s-1)}}$ ----- which is again a kind of Froude number

Rottner then plotted $y = V/\sqrt{d(s-1)}$ against $x = \left[\frac{G}{\rho_s\sqrt{gd^3(s-1)}}\right]^{1/3}$ for various ranges of d/D values. In these parameters, V is in cm./sec., G is in gm./sec./cm. width, d is in cm. The exponent 1/3 was chosen for the graphs in order to render the various degrees of scatter comparable. A sample of Rottner's plot is shown in FIGURE A-30. From these plots he developed an equation of the form

$$x = a_1 y - b_1 \tag{4.5.1}$$

where x and y are as defined before and $a_1$ and $b_1$ are some constants. Now for charge $C \to 0$ the value of G in Rottner's parameter tends to zero. Therefore $x \to 0$. Therefore from Equation 4.5.1, for incipient condition

$$y = \frac{b_1}{a_1}$$

or

$$\frac{V}{\sqrt{d(s-1)}} = \frac{b_1}{a_1} \tag{4.5.2}$$

Squaring and dividing both sides by g in cm./sec.$^2$.
We get

$$\frac{V^2}{gd(s-1)} = \left(\frac{b_1}{a_1}\right)^2 \frac{1}{g} \qquad (4.5.3)$$

The left hand side of Equation 4.5.3 is the parameter plotted against d/D in this analysis.
From his equation

$$x = a_1 y - b_1$$

Rottner calculated the optimum values for the coefficients $a_1$ and $b_1$ by using the method of least squares and from this he deduced the characteristic $b_1/a_1$ for incipient entrainment condition. His tabulated values are reproduced in Table 4-1. From these tabulated values, $V^2/gd(s-1)$ values were calculated by using the Equation 4.5.3 taking g as 981 cm./sec.$^2$. In FIGURE 4.20 the plot of $V^2/gd(s-1)$ against d/D for these values is shown. The curve is in full agreement with other plots of this analysis in the d/D range of 10-100. In his paper Rottner remarked that the slope of the plot $V^2/(s-1)gd$ Vs. d/D is not constant but seems to increase with d/D. This is also noticed in FIGURE 4.20.

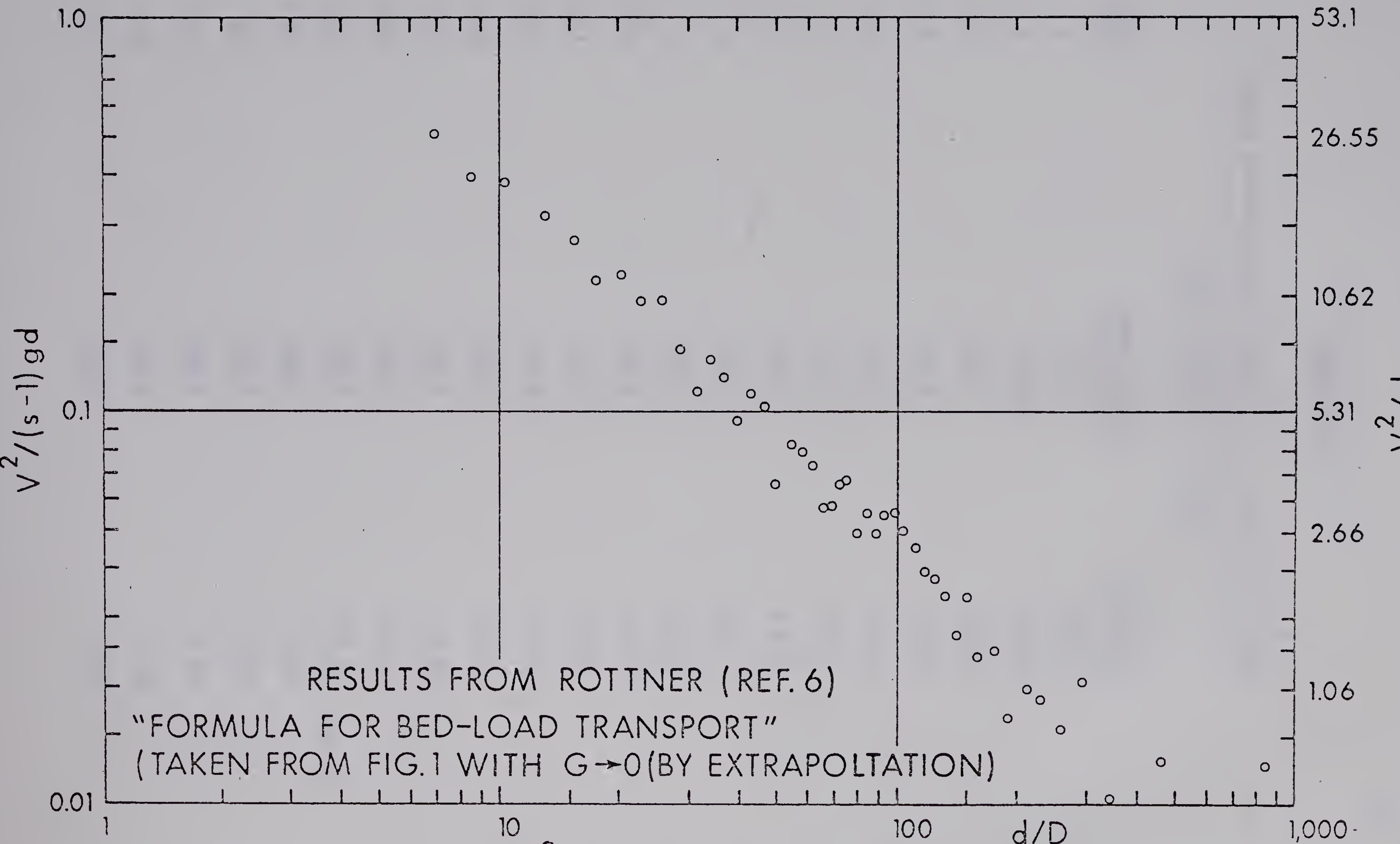



FIG. 4-20 PLOT OF $V^2/(s-1)gd$ vs. $d/D$. DEDUCED FROM ROTTNER'S ANALYSIS

TABLE 4-1

TABLE SHOWING d/D AND $b_1/a_1$ VALUES ADOPTED FROM ROTTNER (1959)

| * Page | Mean (d/D) | ($b_1/a_1$) |
|---|---|---|
| 1 | 6.71 | 22.3 |
| 2 | 8.38 | 19.6 |
| 3 | 10.1 | 19.4 |
| 4 | 12.9 | 17.6 |
| 5 | 15.3 | 16.3 |
| 6 | 17.3 | 14.6 |
| 7 | 20.1 | 14.8 |
| 8 | 22.6 | 13.7 |
| 9 | 25.6 | 13.7 |
| 10 | 28.3 | 11.9 |
| 11 | 31.3 | 10.5 |
| 12 | 34.0 | 11.6 |
| 13 | 36.7 | 11.0 |
| 14 | 39.7 | 9.69 |
| 15 | 43.0 | 10.4 |
| 16 | 46.6 | 10.1 |
| 17 | 49.8 | 8.01 |
| 18 | 54.2 | 8.97 |
| 19 | 58.1 | 8.82 |
| 20 | 61.5 | 8.49 |
| 21 | 65.3 | 7.48 |

TABLE 4-1 CONTINUED

| * Page | Mean (d/D) | $(b_1/a_1)$ |
|---|---|---|
| 22 | 69.0 | 8.03 |
| 23 | 71.9 | 7.52 |
| 24 | 75.7 | 8.15 |
| 25 | 79.6 | 6.95 |
| 26 | 84.5 | 7.39 |
| 27 | 89.1 | 6.96 |
| 28 | 93.7 | 7.3 |
| 29 | 99.7 | 7.37 |
| 30 | 105 | 7.00 |
| 31 | 112 | 6.66 |
| 32 | 119 | 6.2 |
| 33 | 126 | 6.08 |
| 34 | 134 | 5.77 |
| 35 | 142 | 5.14 |
| 36 | 151 | 5.75 |
| 37 | 161 | 4.83 |
| 38 | 178 | 4.92 |
| 39 | 193 | 4.05 |
| 40 | 215 | 4.38 |
| 41 | 233 | 4.26 |
| 42 | 262 | 3.90 |
| 43 | 298 | 4.46 |

TABLE 4-1 CONTINUED

| * Page | Mean (d/D) | $(b_1/a_1)$ |
|---|---|---|
| 44 | 350 | 3.06 |
| 45 | 472 | 3.56 |
| 46 | 870 | 3.51 |

* NOTE: "Page" in Rottner's analysis stands for various plots he classified according to various ranges of d/D.

CHAPTER V

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 CONCLUSIONS

The following conclusions can be drawn from the results obtained by analysing flume-data and their reasonable consistency with the limited amount of field observations:

(i) In the range of data analysed the behaviour of $V^2/(s-1)gd$ is quite different from that in the range of sand-bed canals and rivers.

(ii) The data in the range $10 < d/{}^m_w D < 100$ fall in a band whose centre-line can be represented by:

$$\frac{V^2}{(s-1)gd} = 3.7\ (d/{}^m_w D)^{-4/5} \tag{5.1}$$

(iii) The band limits (Line AB and CD in FIGURE 4-6) containing about 95% of points can be represented reasonably by replacing the coefficient 3.7 in Equation 5.1 by 8.3 and 1.8 respectively.

(iv) The regime theory relation

$$\frac{V^2}{(s-1)gd} = \text{fn}\left(\sqrt[3]{\nu g(s-1)}\frac{D}{\nu}\right) \tag{5.2}$$

can be seen coming into effect above values of $d/{}_{w}^{m}D$ in the neighbourhood of 400.

(v) The change from Equation 5.1 to Equation 5.2 is fairly abrupt and seems to be of different types; data are insufficient to permit a definite statement on the types and to reach appreciably into the zone of Equation 5.2.

(vi) The literature does not describe bed-forms sufficiently to show a reason for the phase change from Equation 5.1 to Equation 5.2.

(vii) The scatter of points about equation 5.1 does not appear to be due to the variations in D; but 80% of the data had ${}_{w}^{m}D$ values between 0.2 mm. and 2.0 mm. so a slow variation of $V^2/(s-1)gd$ with D could be hidden. But a variation of $V^2/(s-1)gd$ with C is remarkably noticed.

(viii) A systematic effect of b/d could not be found for $1.10 < b/d < 120$ approximately; neither grain-size distribution expressed by $G_R$, ranging from 1.07 to 4.5, seems to have any systematic effect in the range $10 < d/{}_{w}^{m}D < 100$. But in the range $100 < d/{}_{w}^{m}D < 500$, data with smaller values of $G_R$ seem to fall above those with larger values of $G_R$ (FIGURE 4.5 (a) & 4.5 (b)).

(ix) Light weight materials plotted consistently with the others in terms of $V^2/(s-1)gd$.

## 5.2 RECOMMENDATIONS

The following points merit attention for future research:

(i) The relatively blank range $1 < d/D < 10$ should be investigated in order to make definite statement about the behaviour of $V^2/(s-1)gd$ in this zone.

(ii) Experiments should be repeated with:

a) River-bed sand of standardised grading

b) Coarser materials manufactured to have the standard river sand grading

c) d/D reaching to about 1,500 so as to cover the start of the regime theory phase.

(iii) Special experiments with artificial particles of fixed sizes and shapes (e.g. spheres etc.) and with various specific gravities are recommended.

(iv) Data covering higher amount of bed-load charge should be analysed.

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APPENDIX "A"

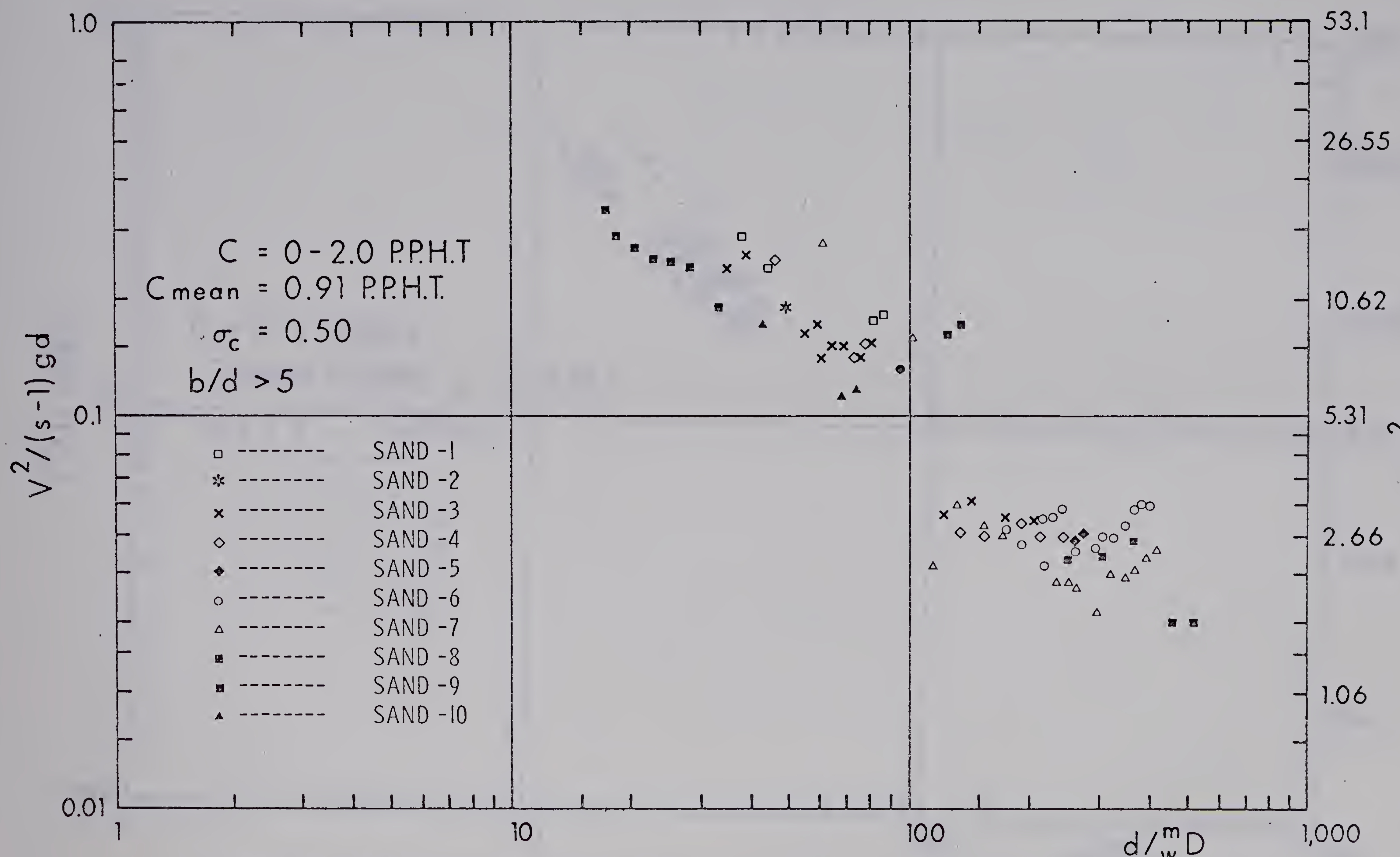



FIG. A-1 PLOT OF $V^2/(s-1)gd$ vs. $d/^m_w D$ FOR U.S.W.E.S. DATA

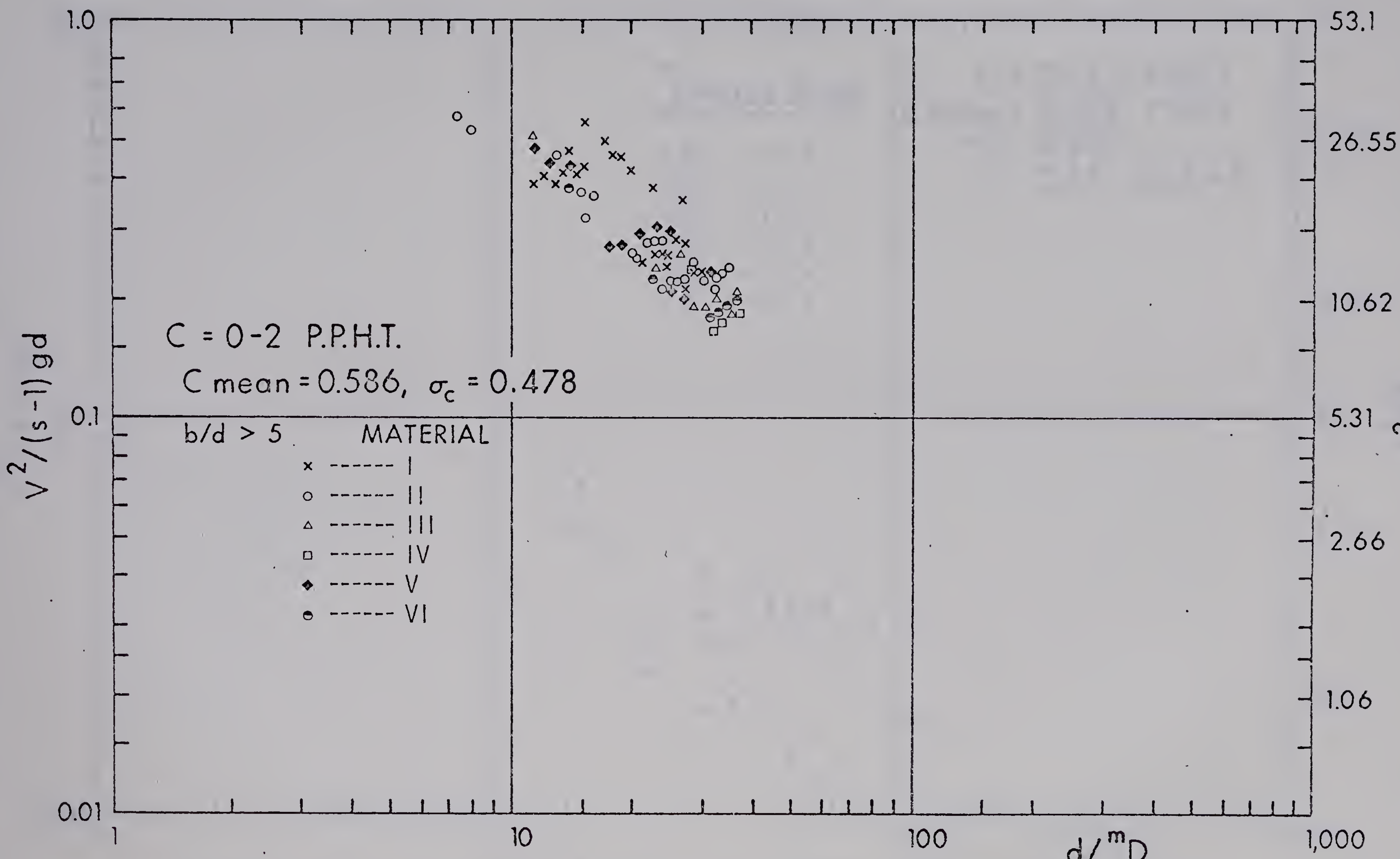



FIG. A-2 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$ FOR T.Y LIU DATA

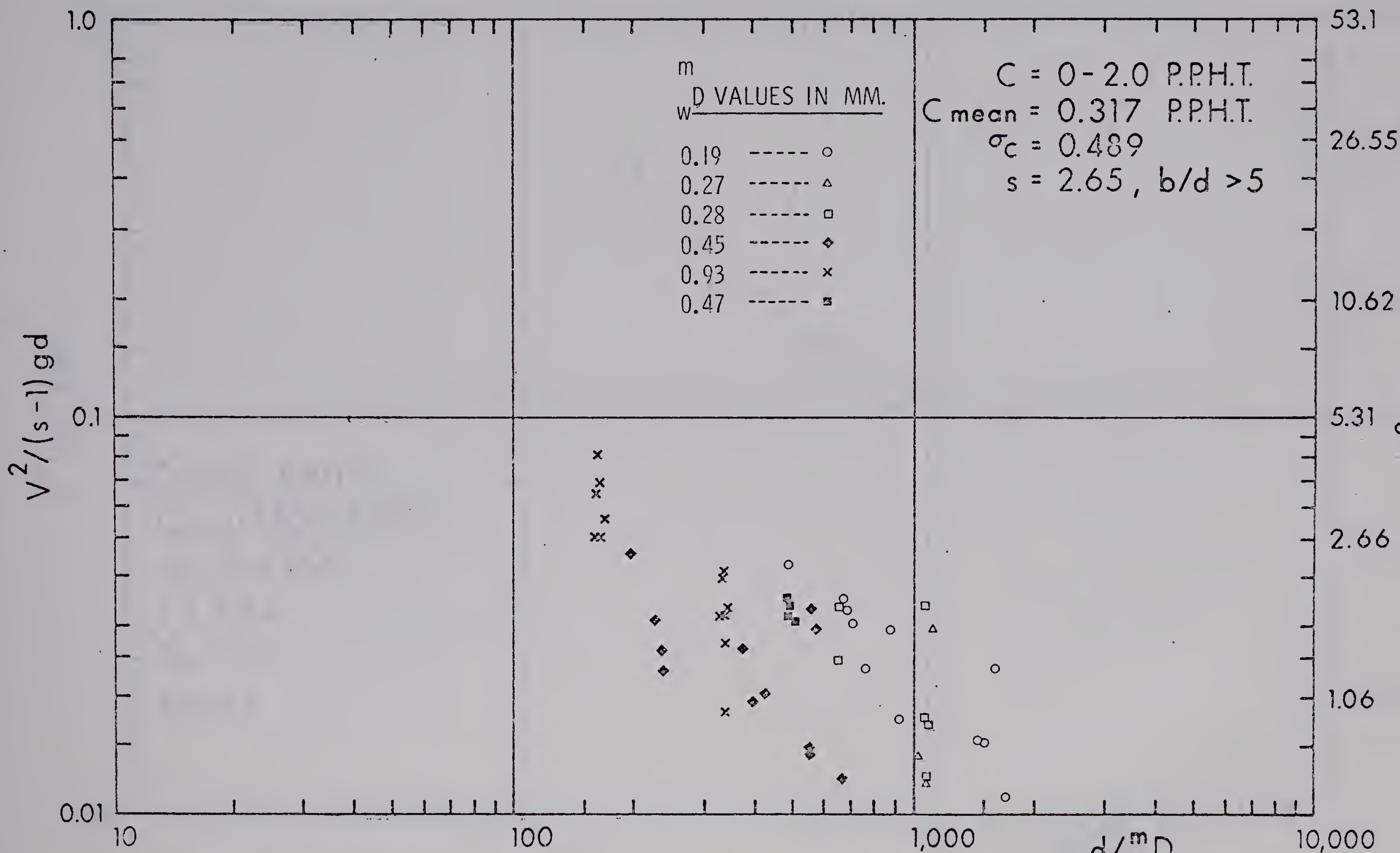



FIG. A-3 PLOT OF $V^2/(s-1)gd$ vs. $d/_w^mD$ FOR C.S.U. DATA

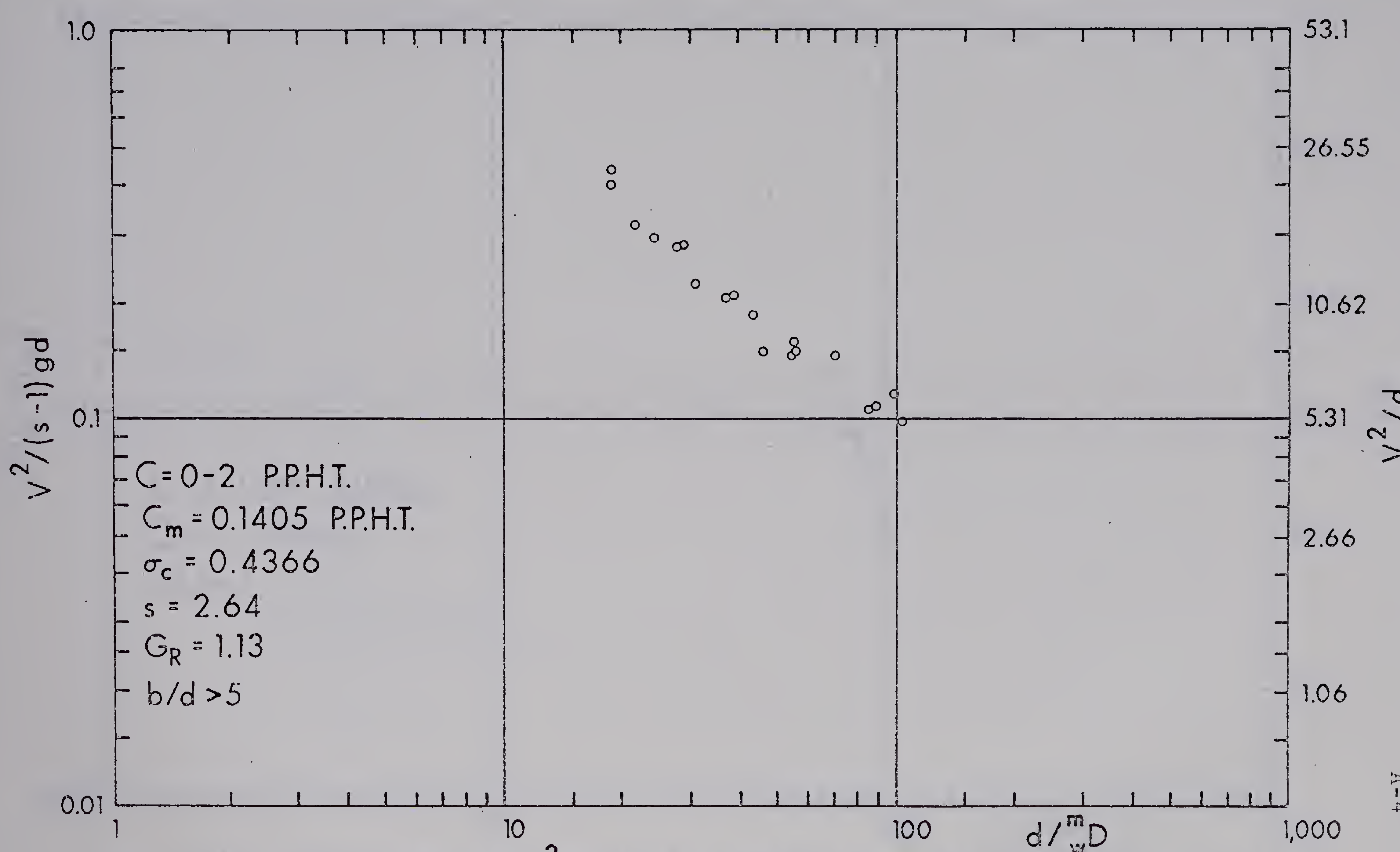



FIG. A-4 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_w D$ FOR B. SINGH DATA

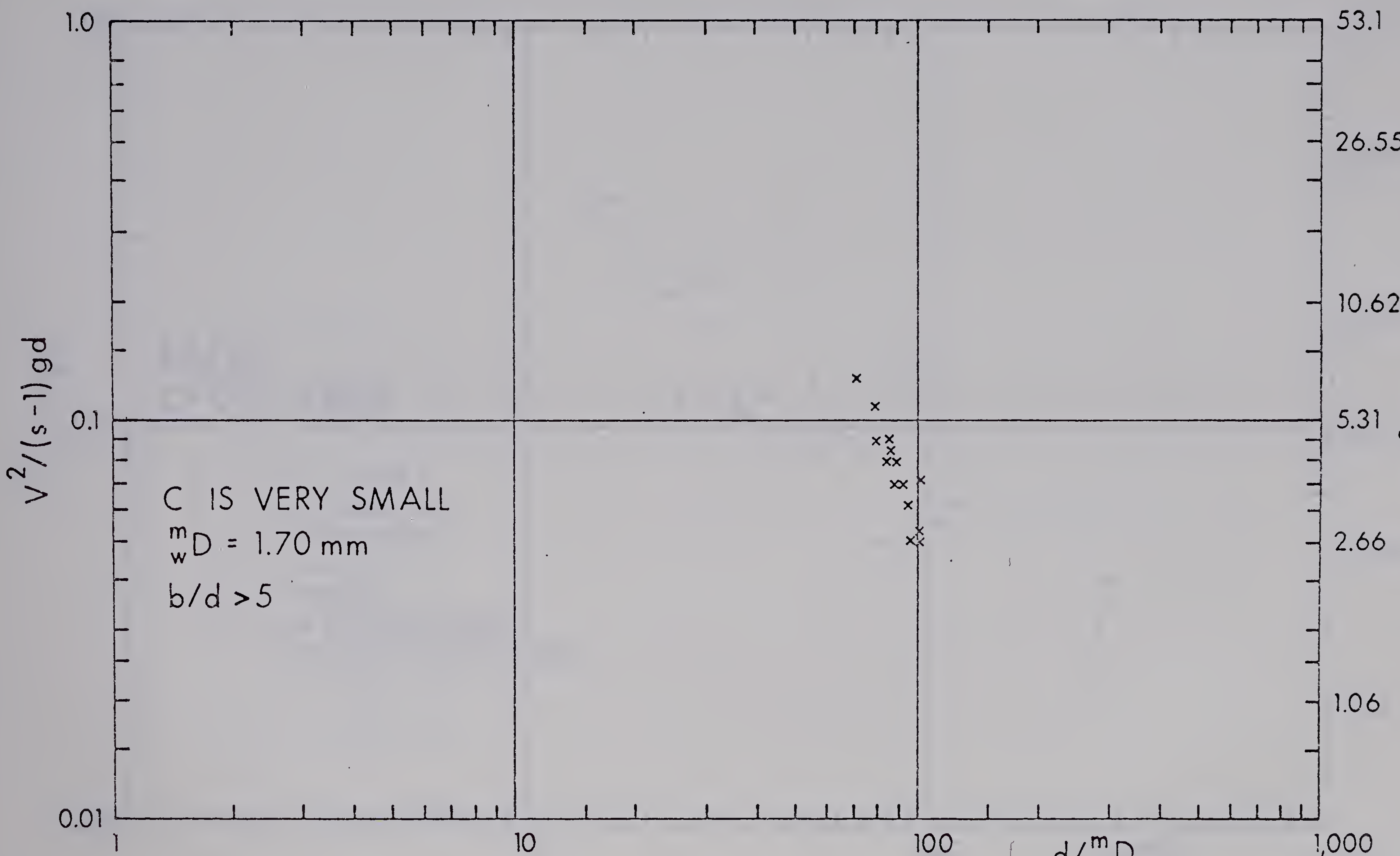



FIG. A-5 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ FOR M.A. QURESHI'S DATA

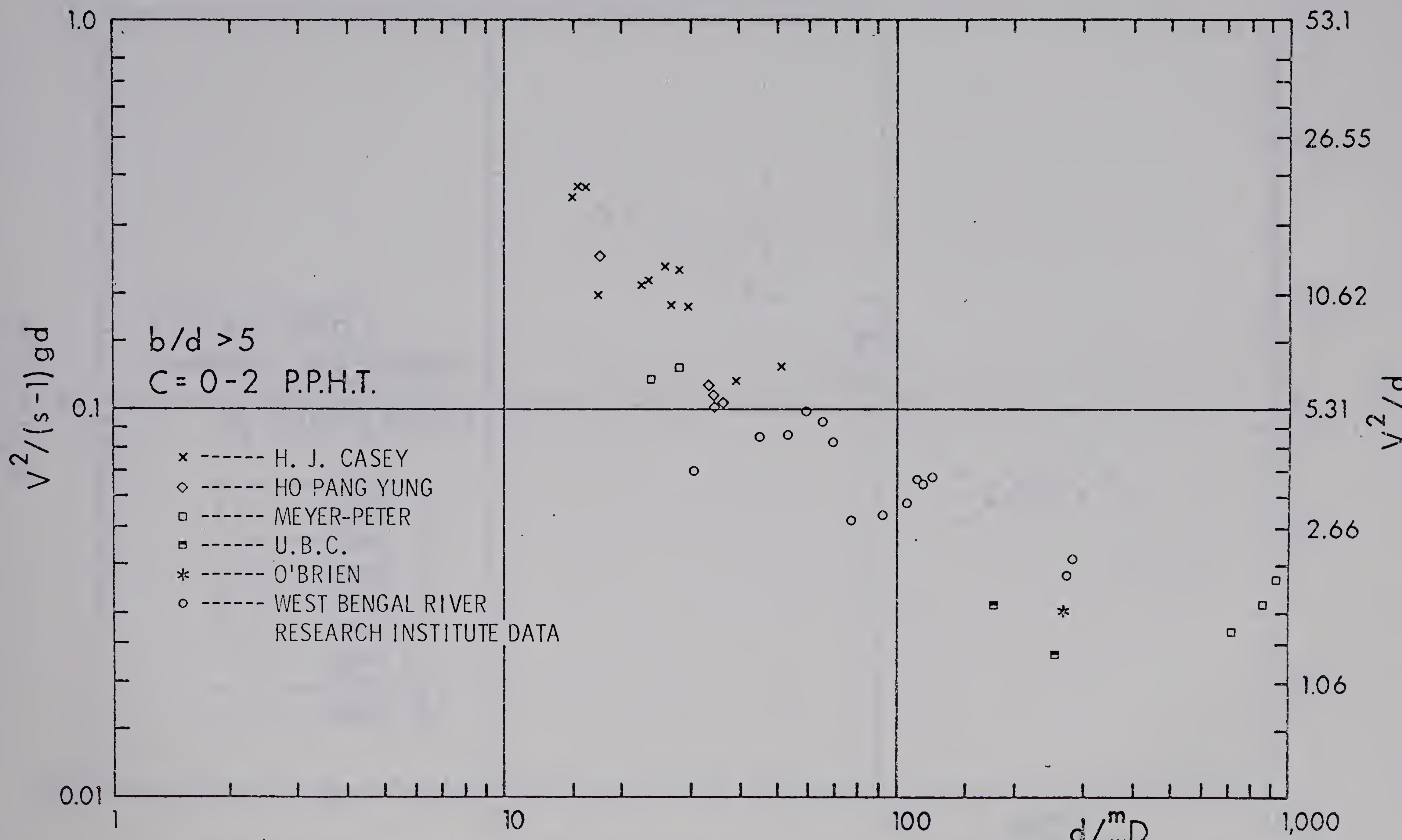



FIG. A-6 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$

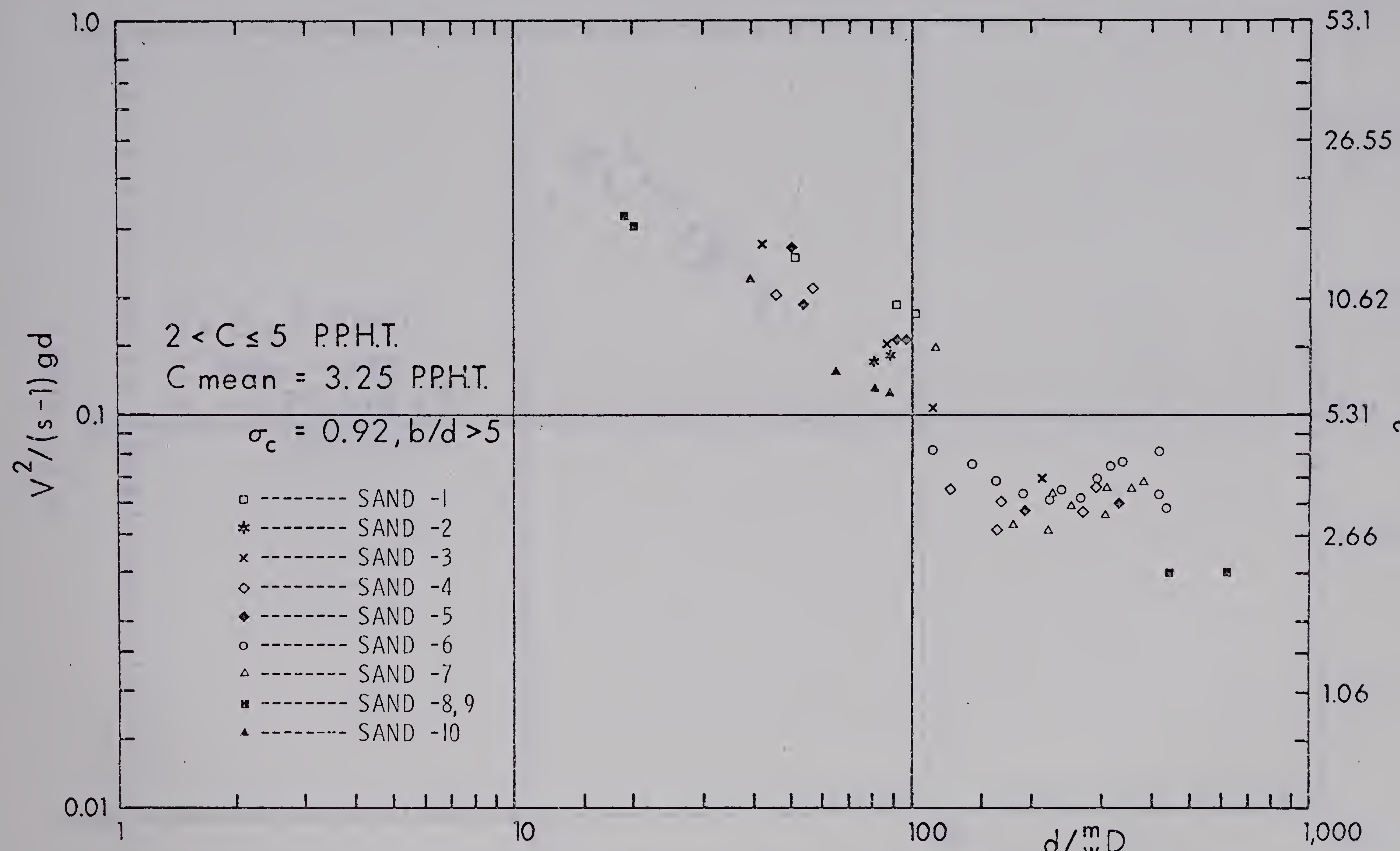



FIG. A-7 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$ FOR U.S.W.E.S. DATA

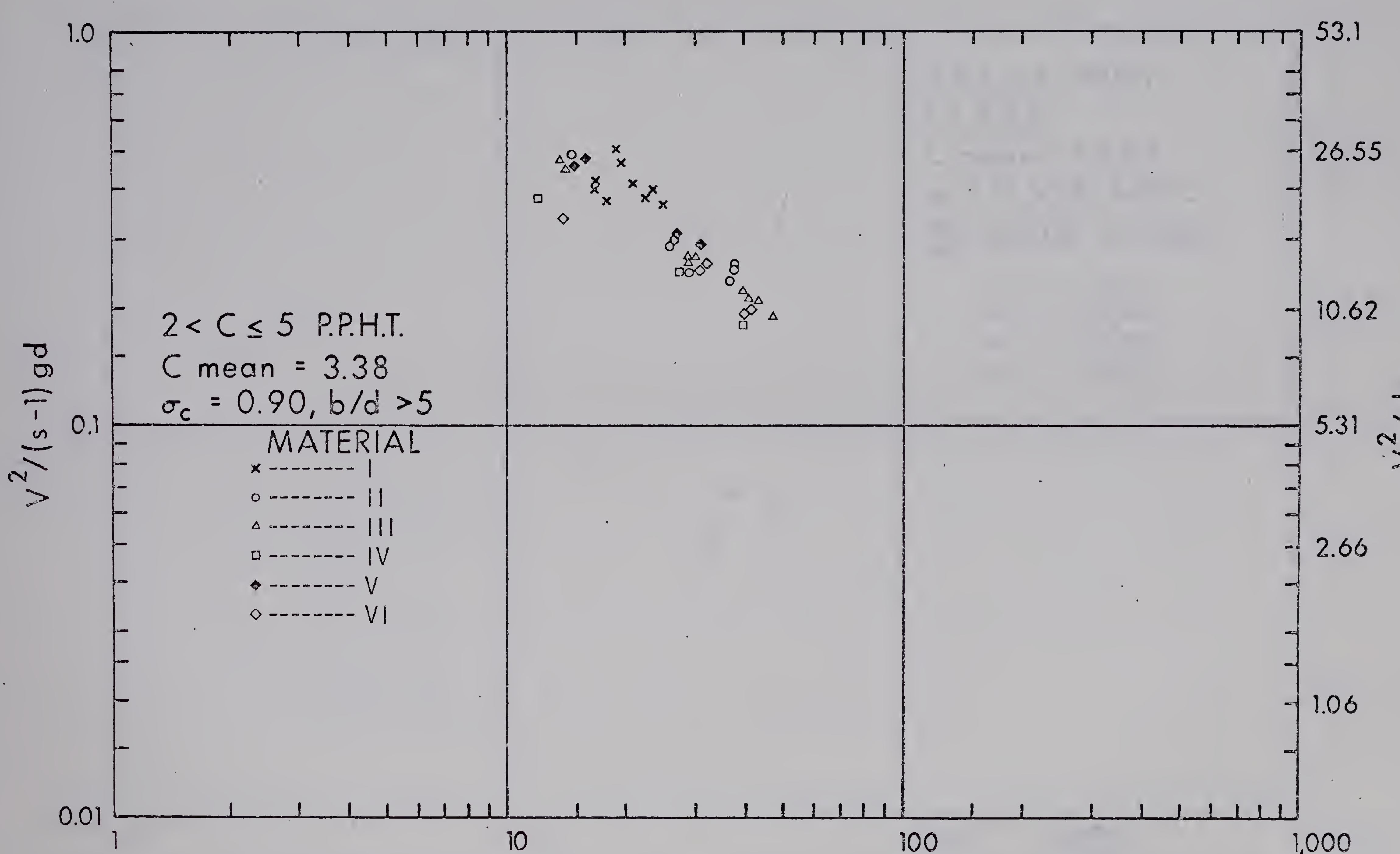



FIG. A-8 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$ FOR T.Y. LIU DATA

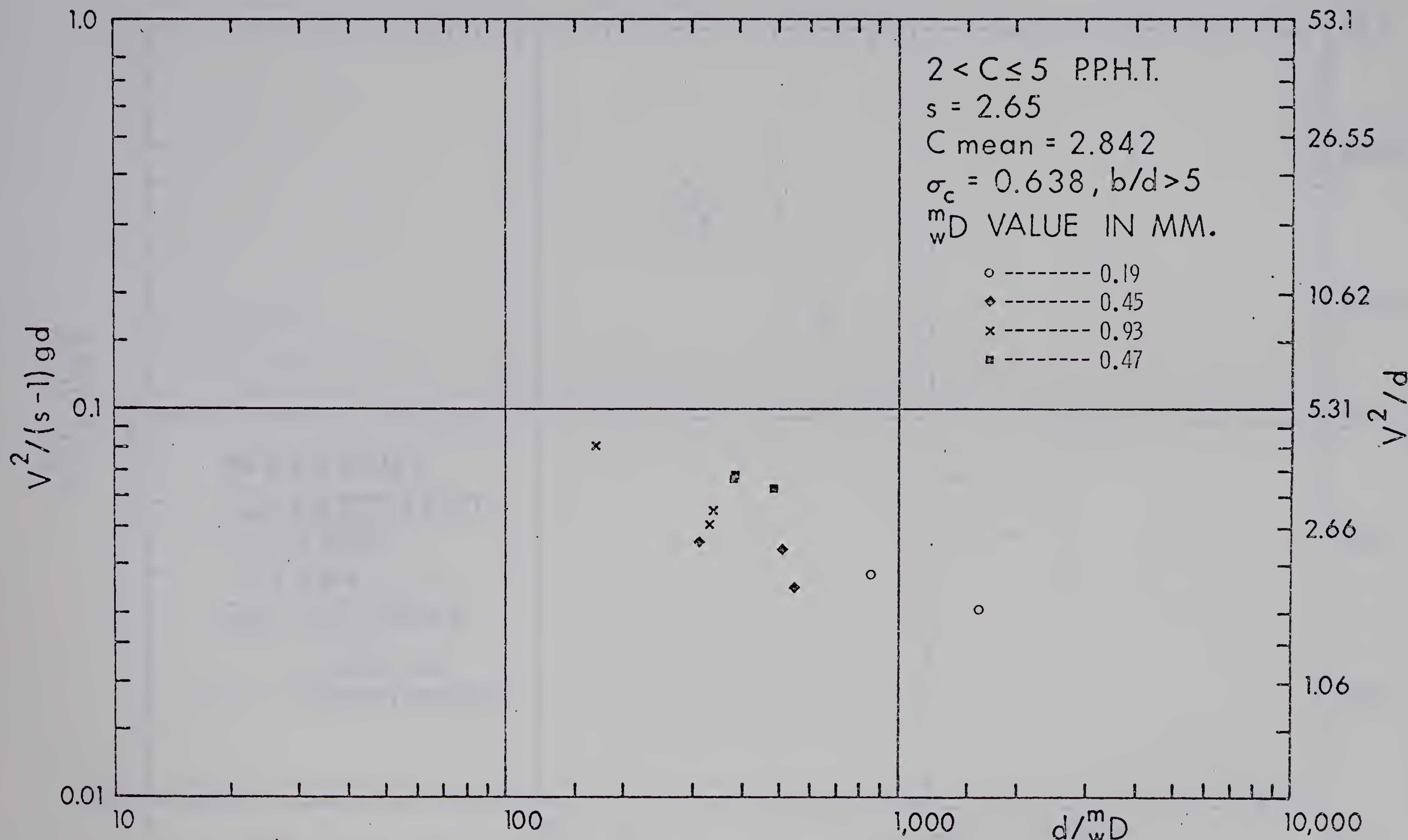



FIG. A-9 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ FOR COLORADO STATE UNIVERSITY DATA

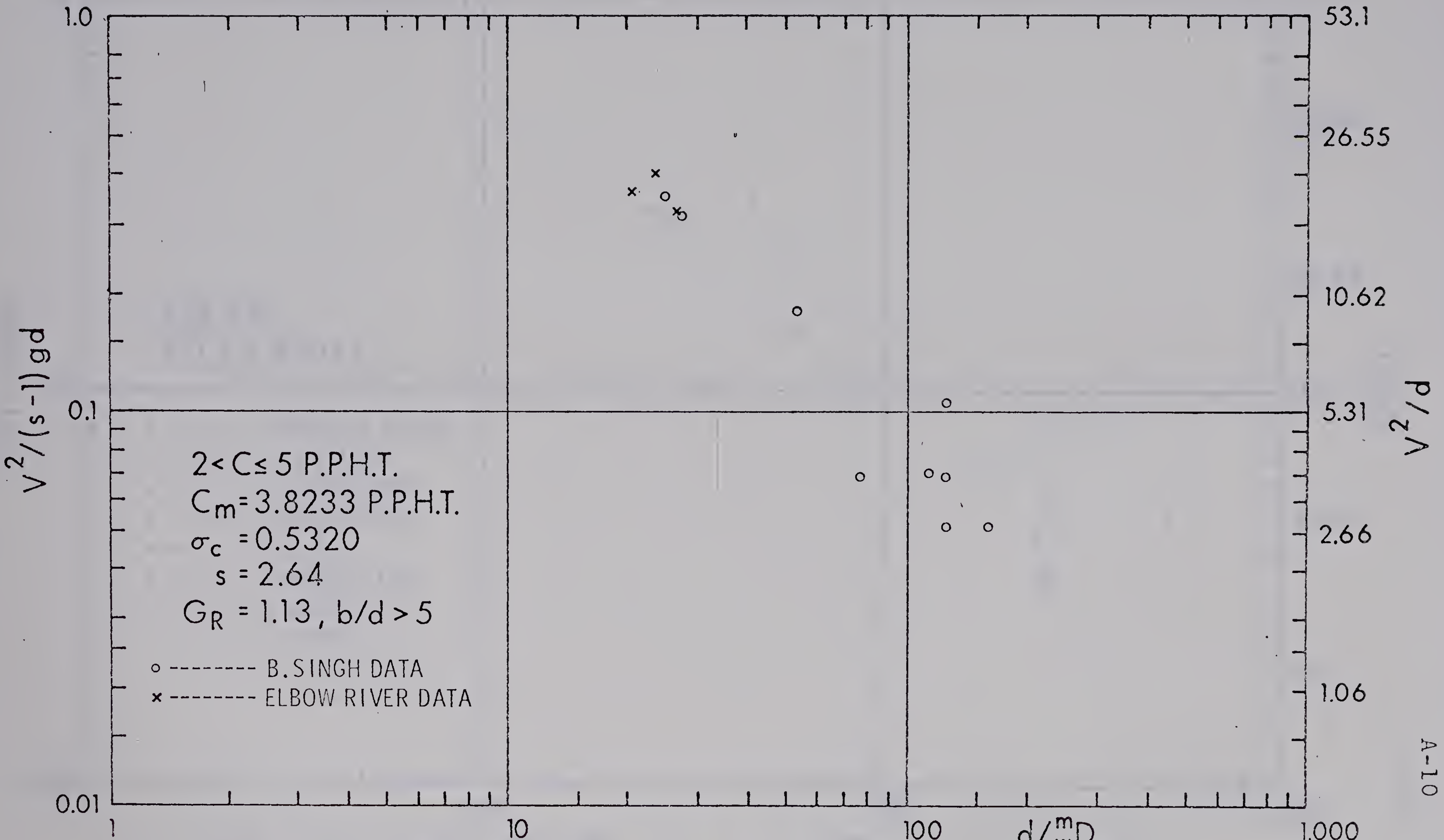



FIG. A-10 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^{m}_{w}D$ FOR B. SINGH AND ELBOW RIVER DATA

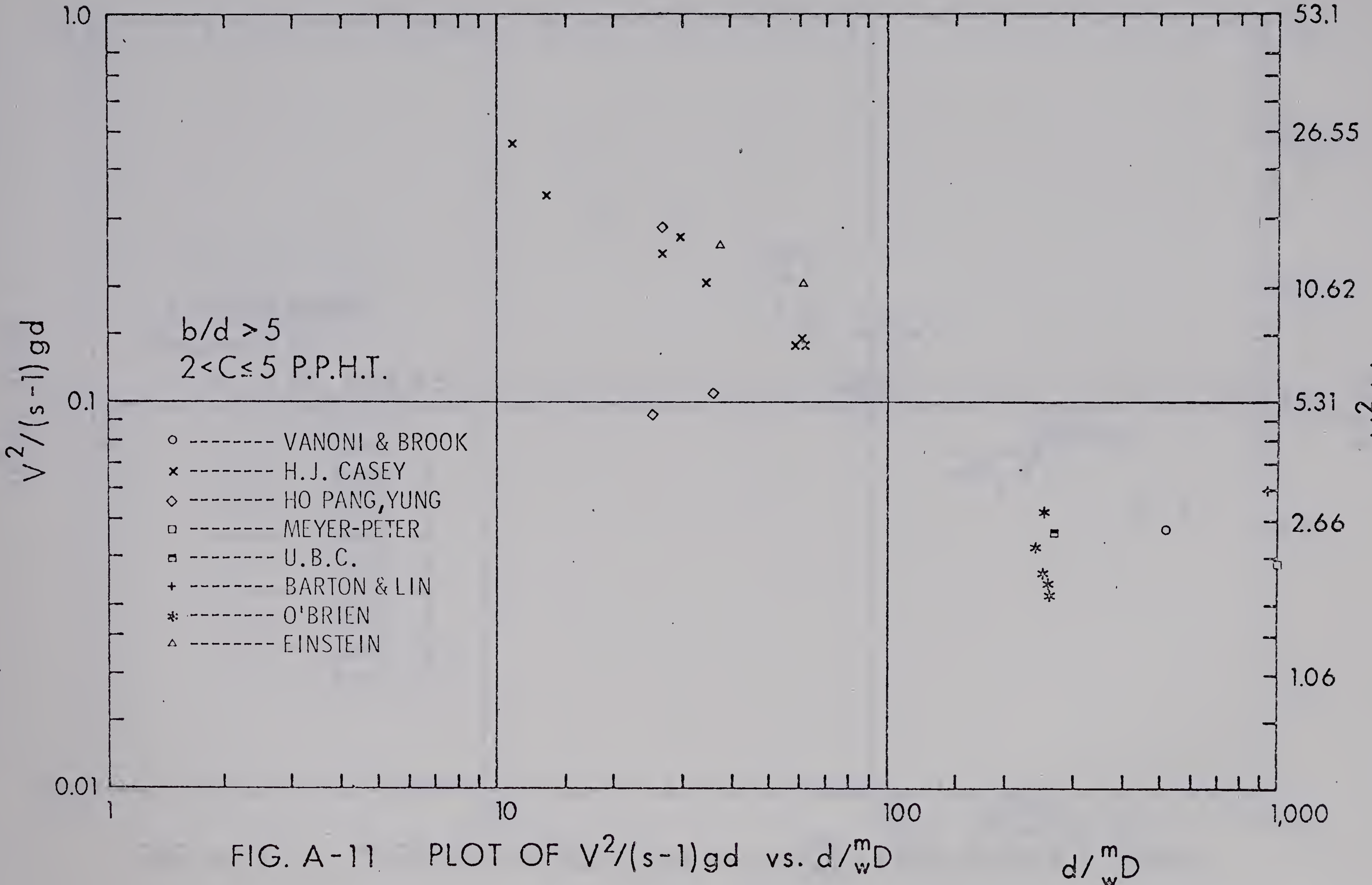



FIG. A-11 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$

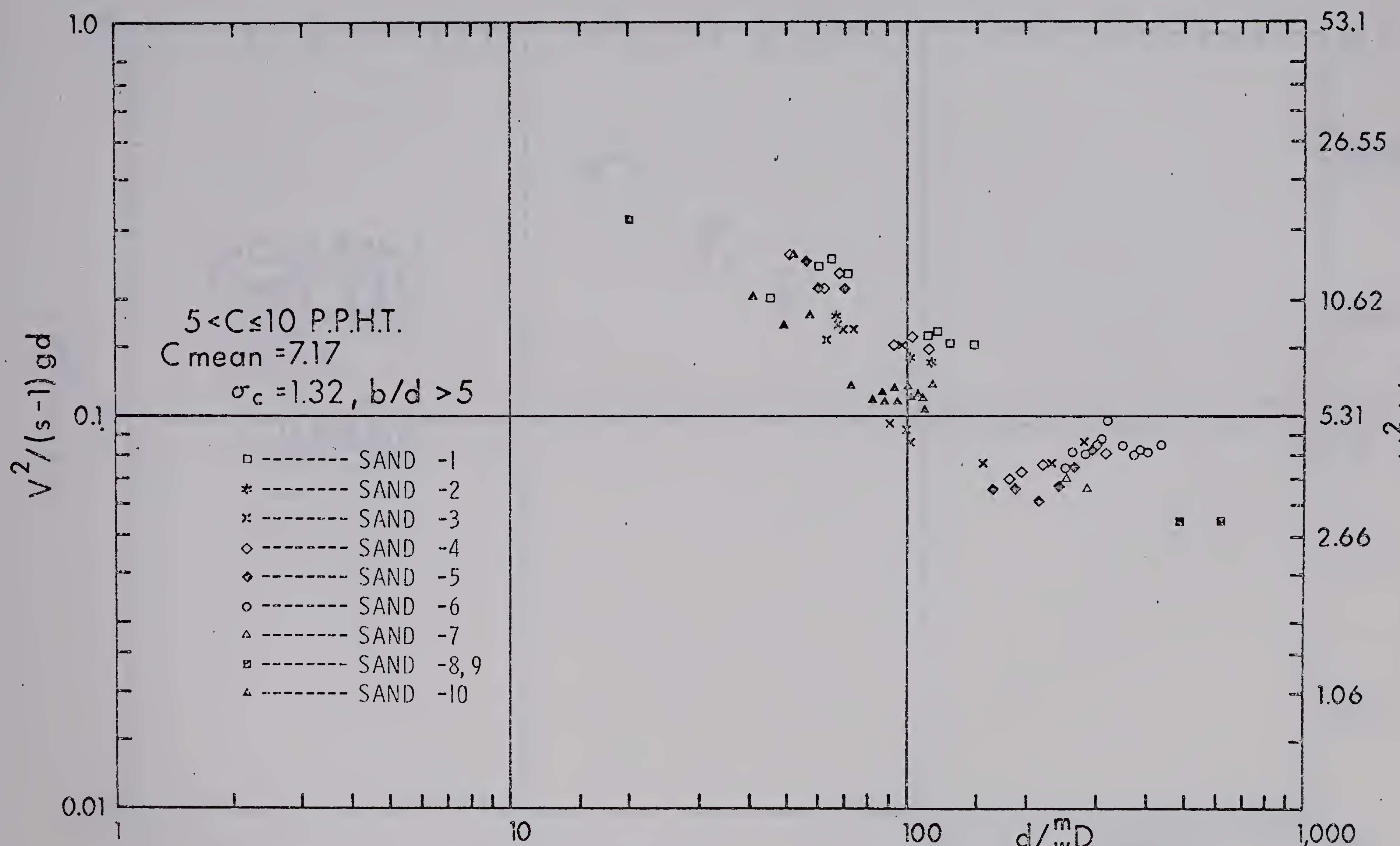



FIG. A-12 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$ FOR U.S.W.E.S. DATA

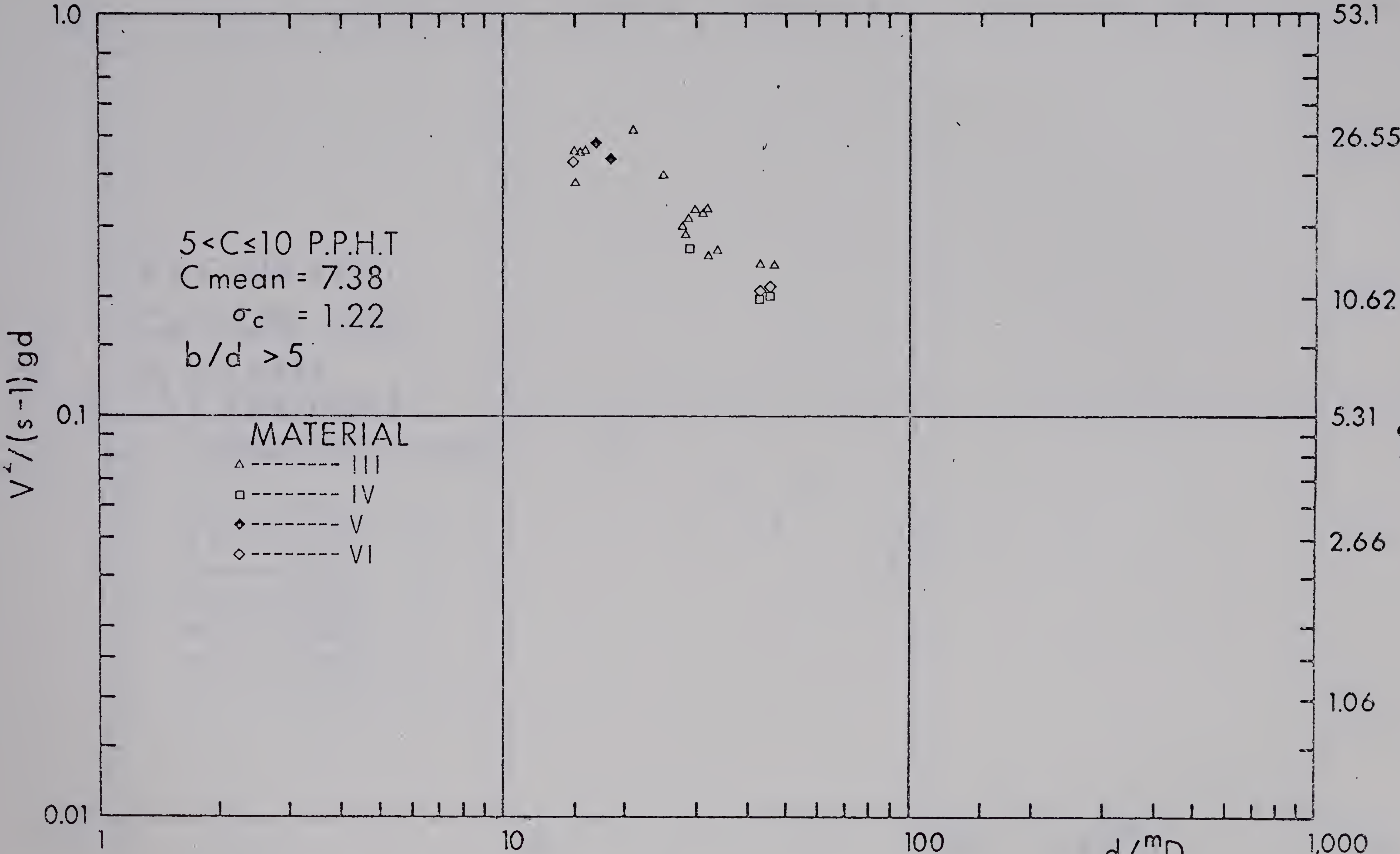



FIG. A-13 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$ FOR T.Y.LIU DATA

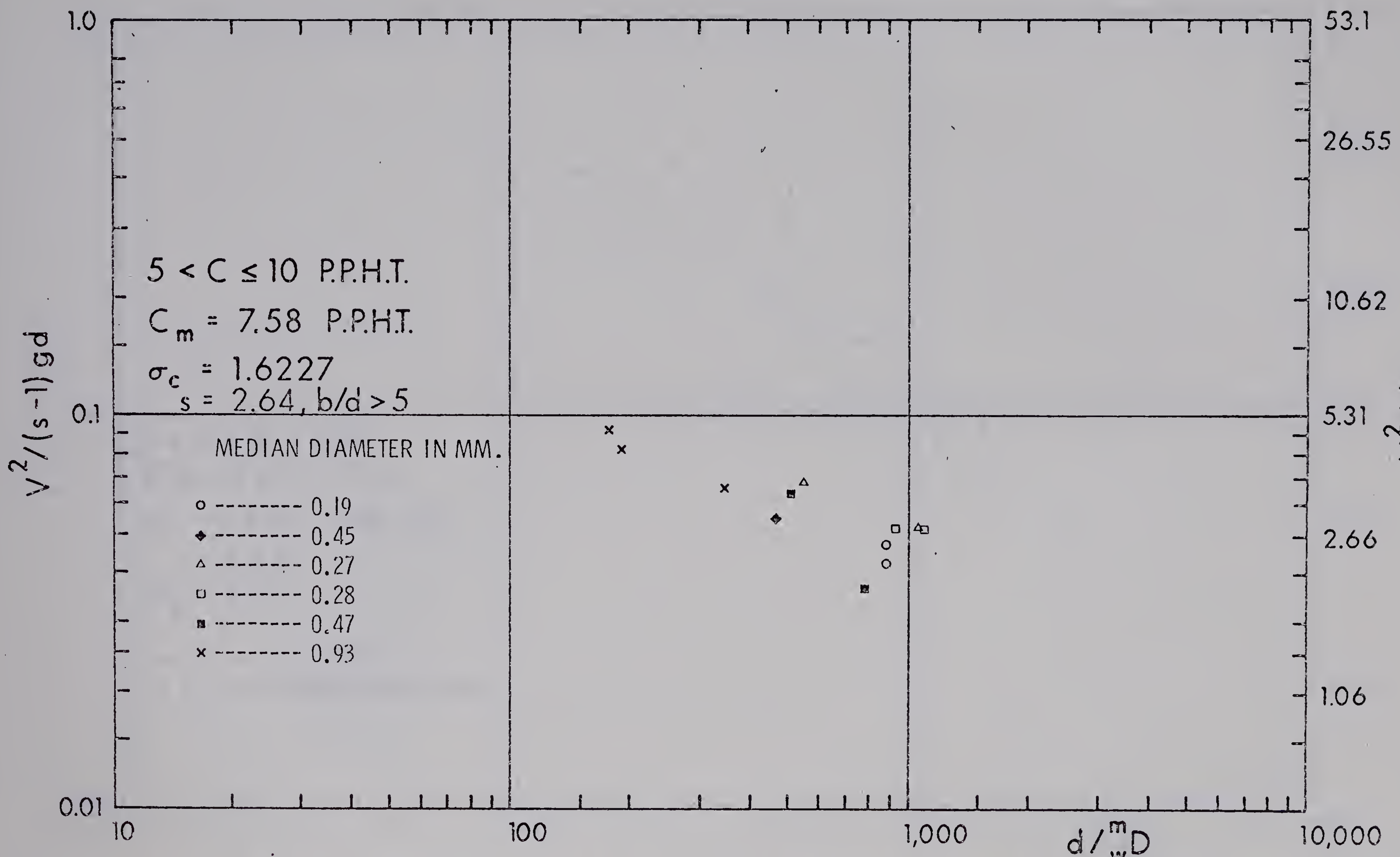



FIG. A-14 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$ FOR C.S.U. DATA

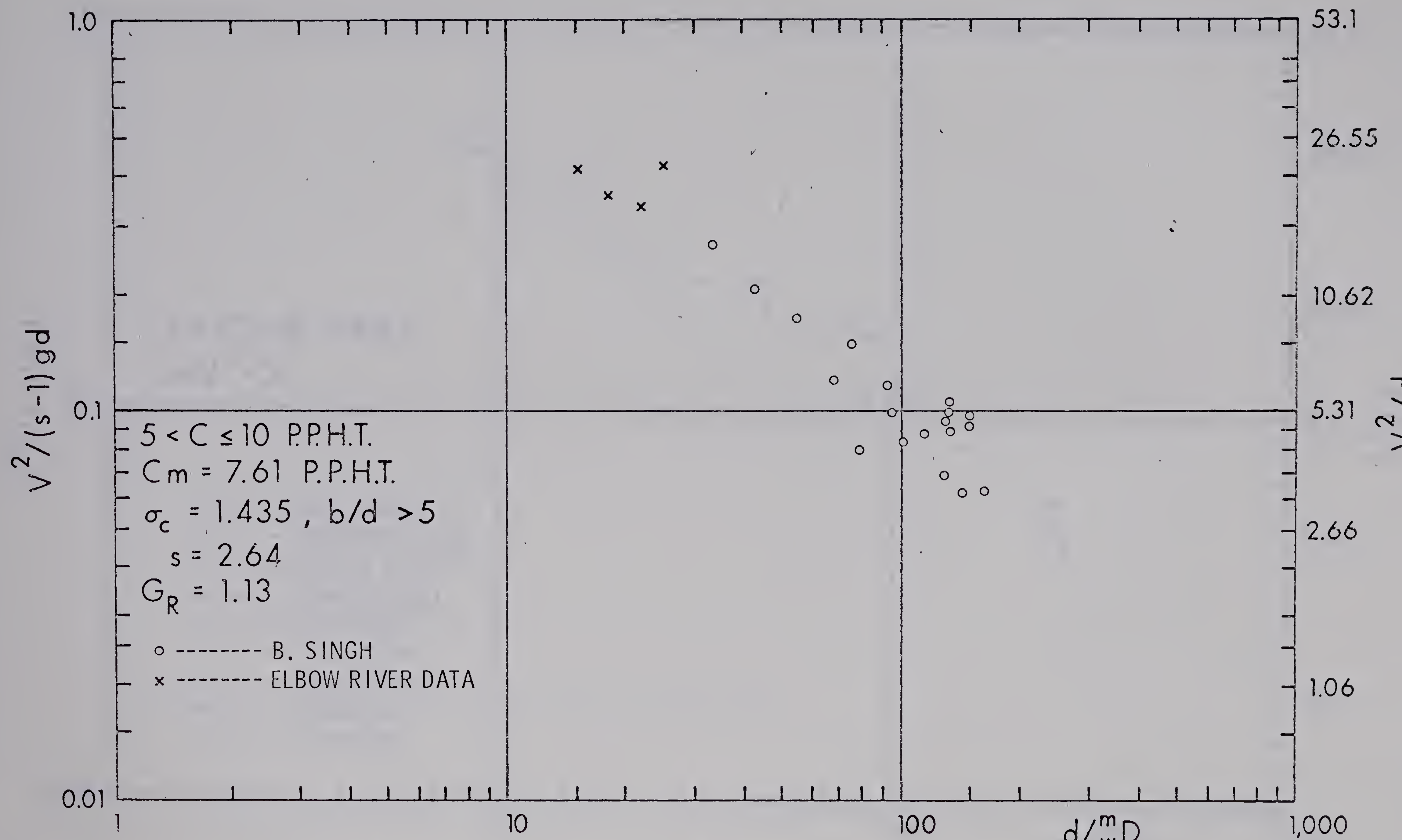



FIG. A-15 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^{m}_{w}D$ FOR B. SINGH & ELBOW RIVER DATA

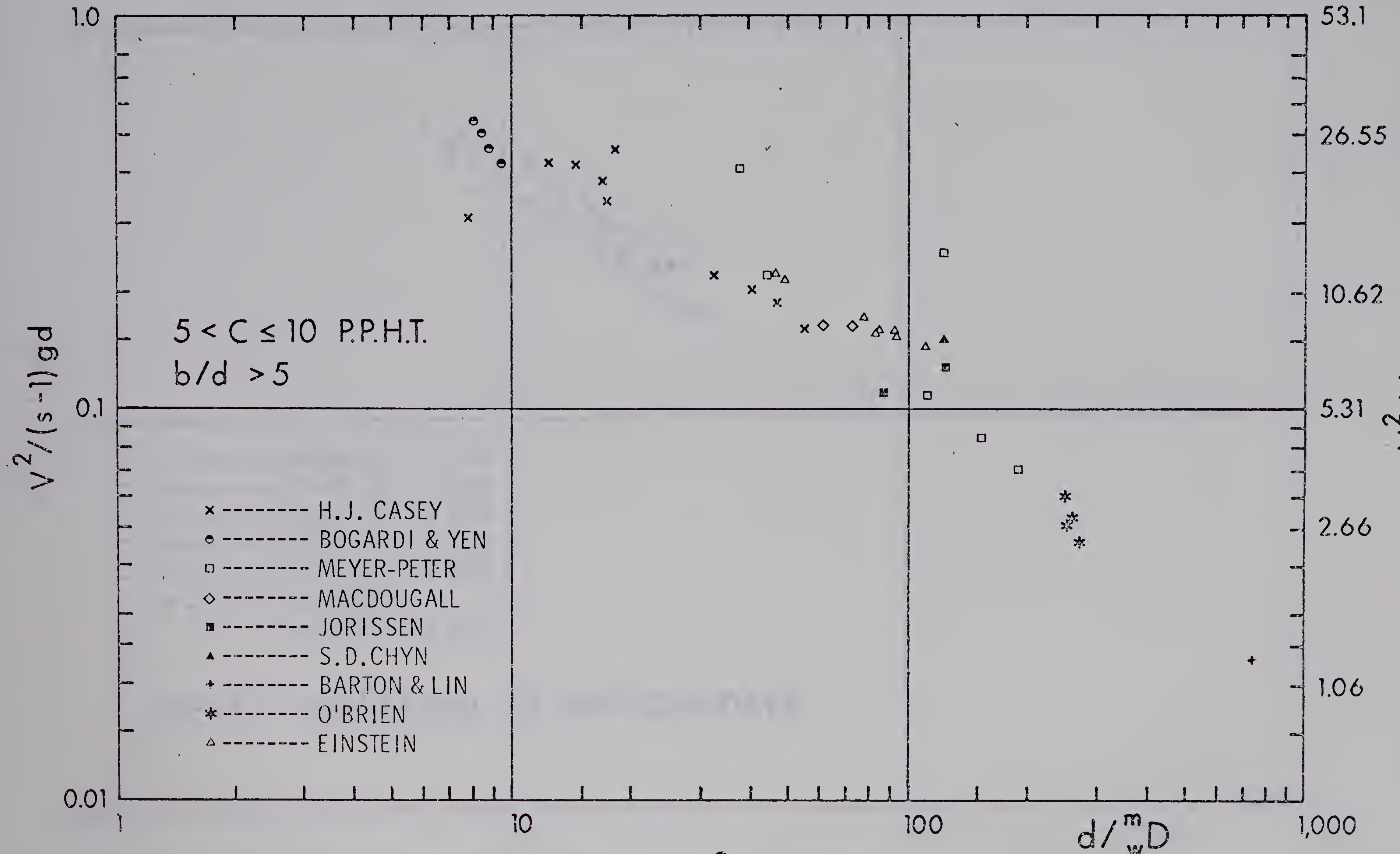



FIG. A-16 PLOT OF $V^2/(s-1)\,gd$ vs. $d/^m_wD$

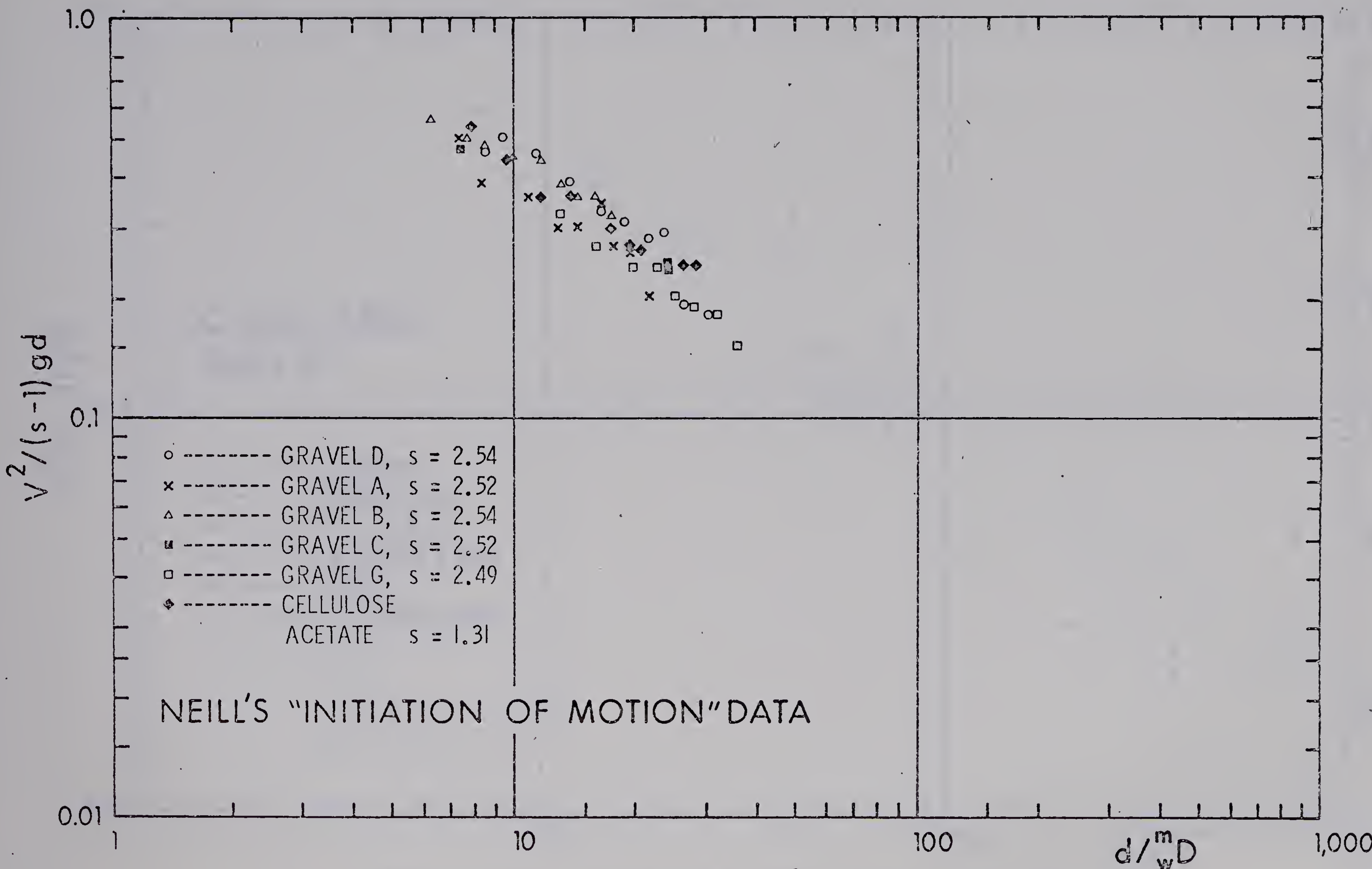



FIG. A-17 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_wD$

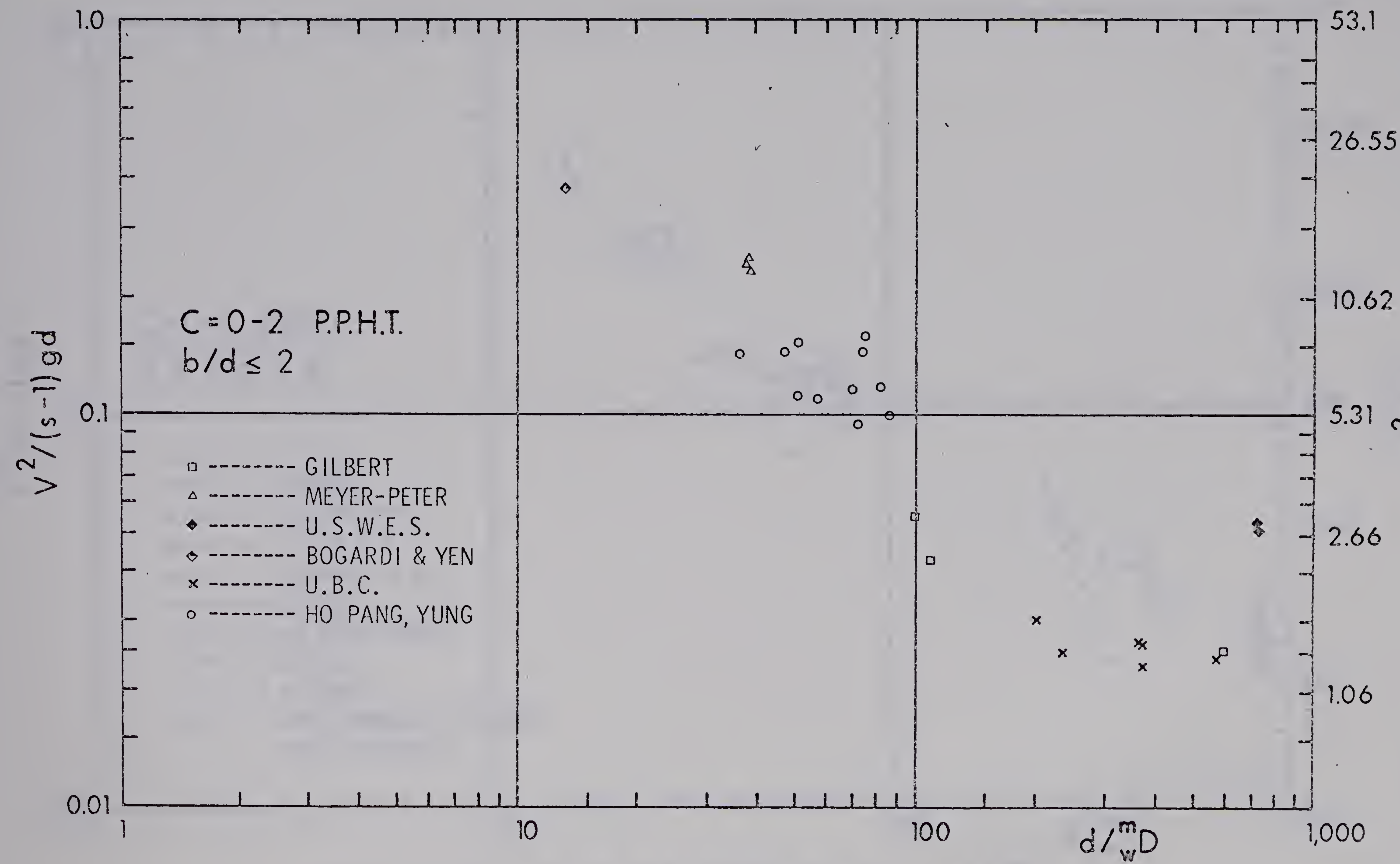



FIG. A-18 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$

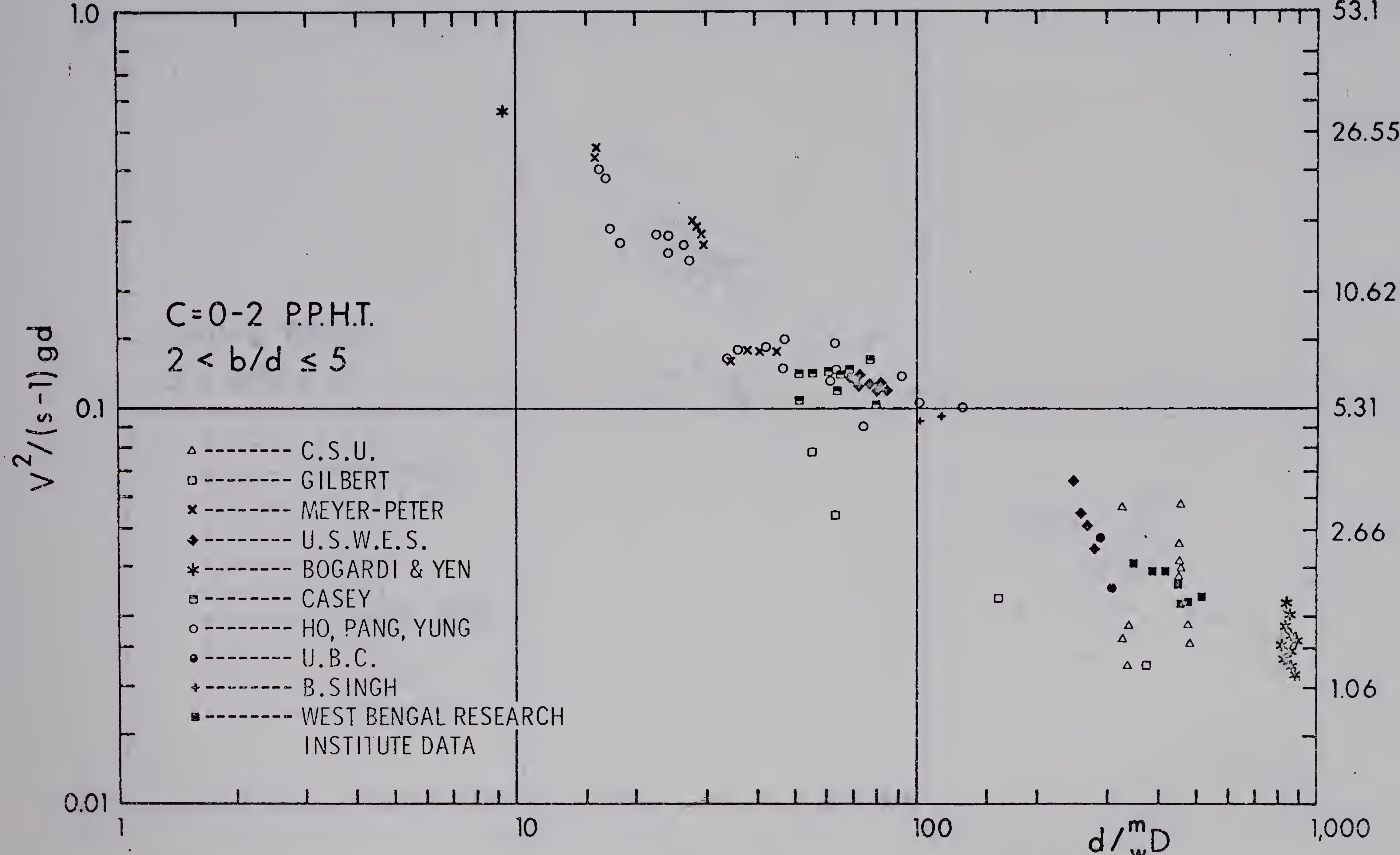



FIG. A-19 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_wD$

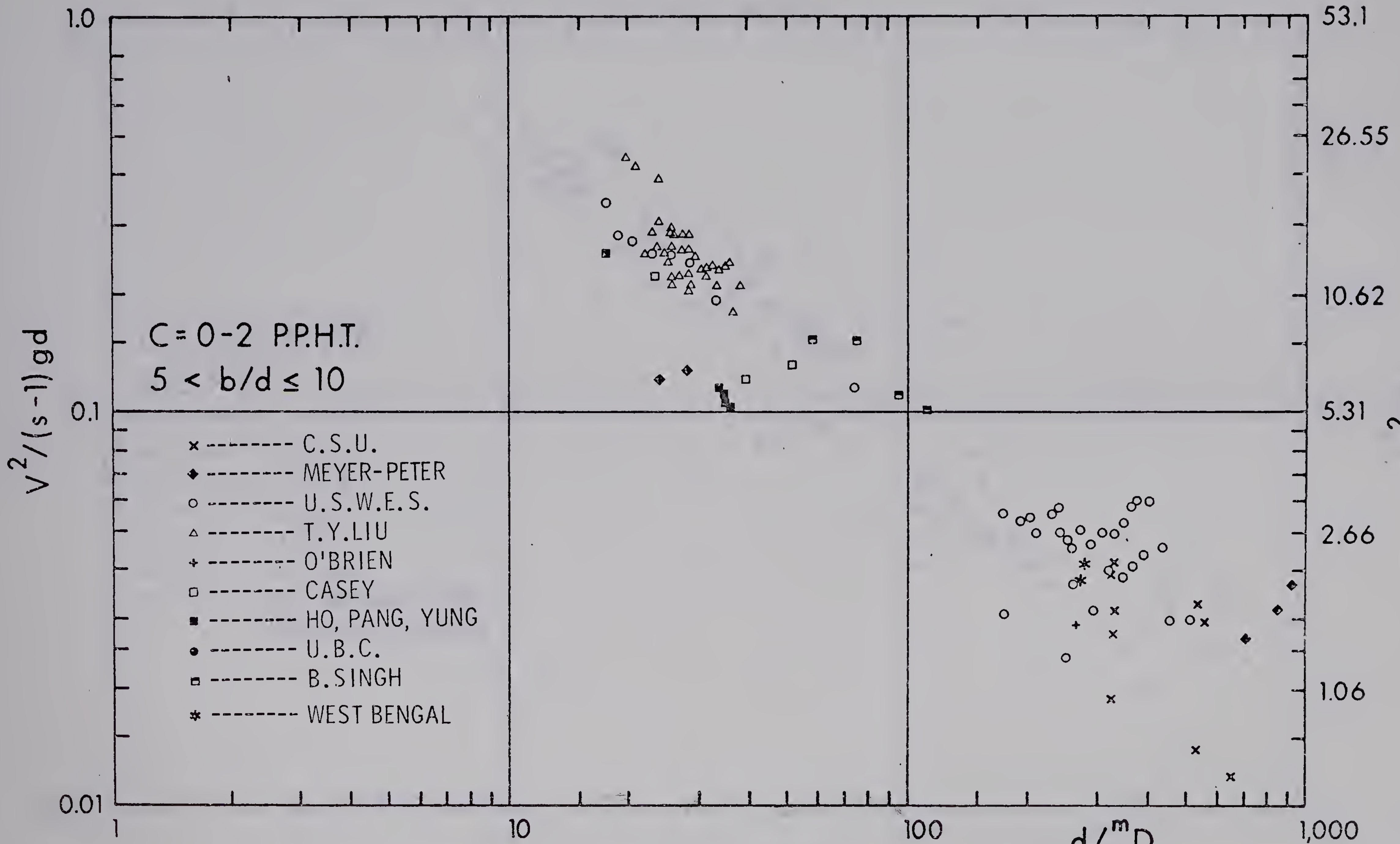



FIG. A-20 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_wD$

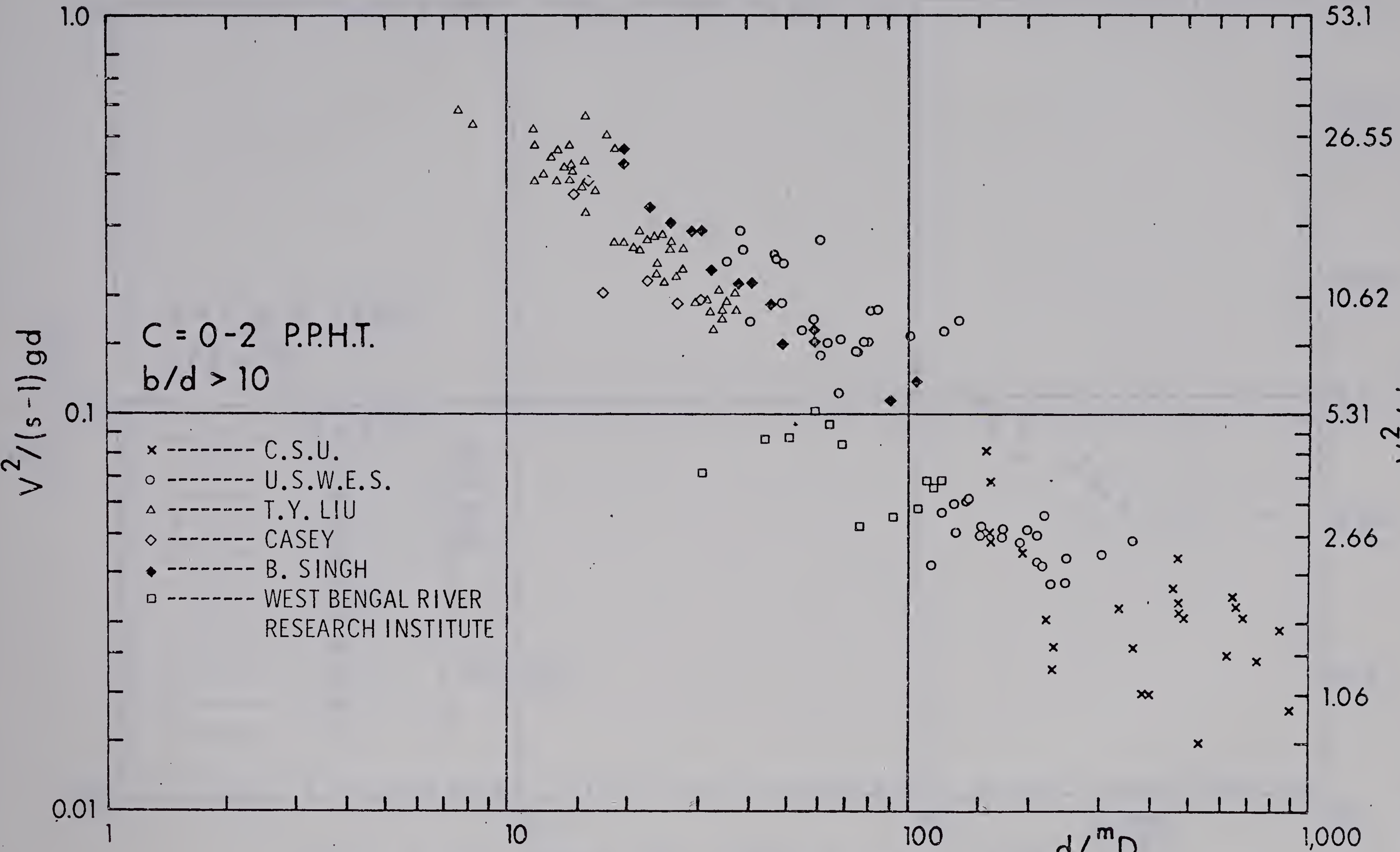



FIG. A-21 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^{m}_{w}D$

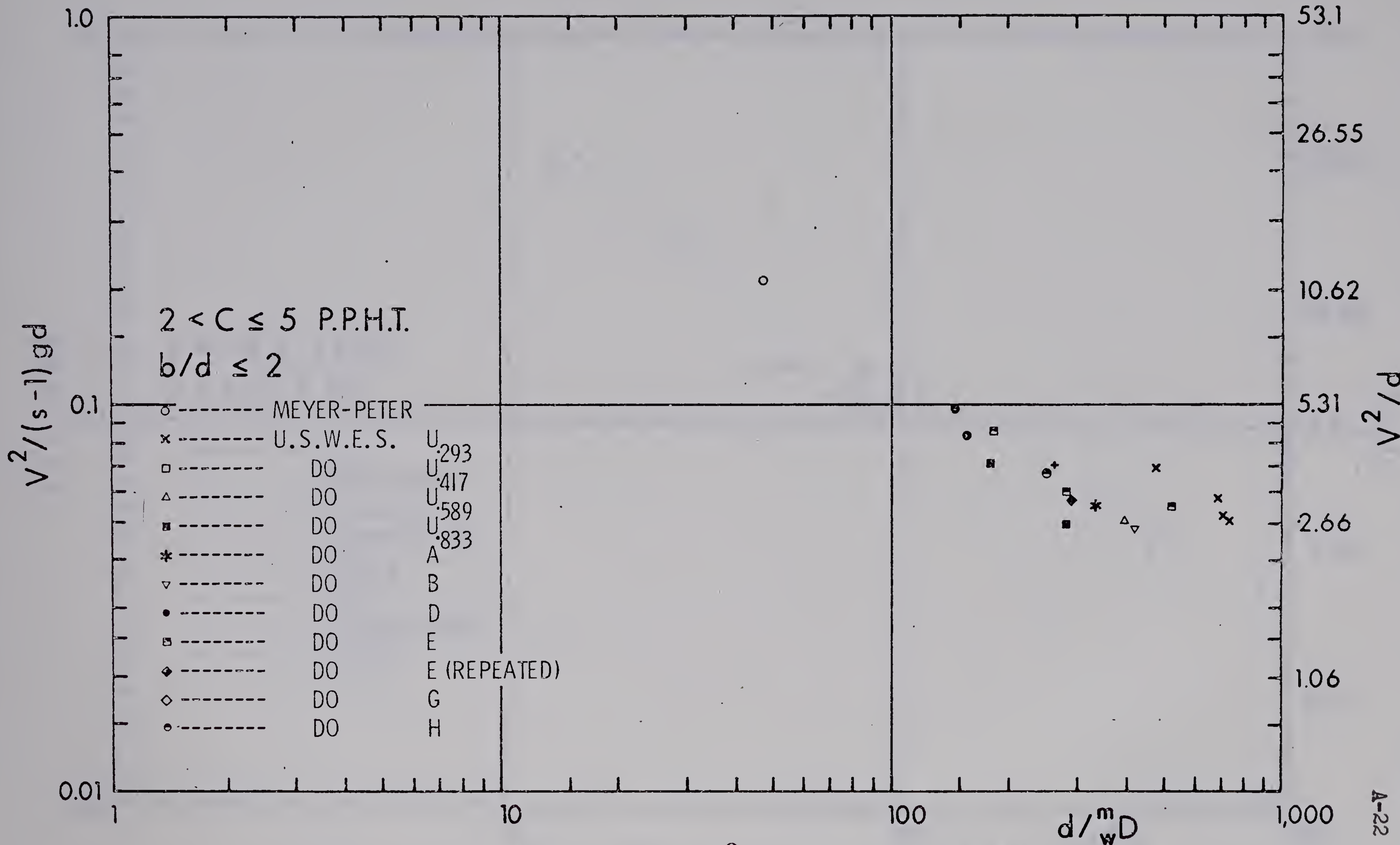



FIG. A-22 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$

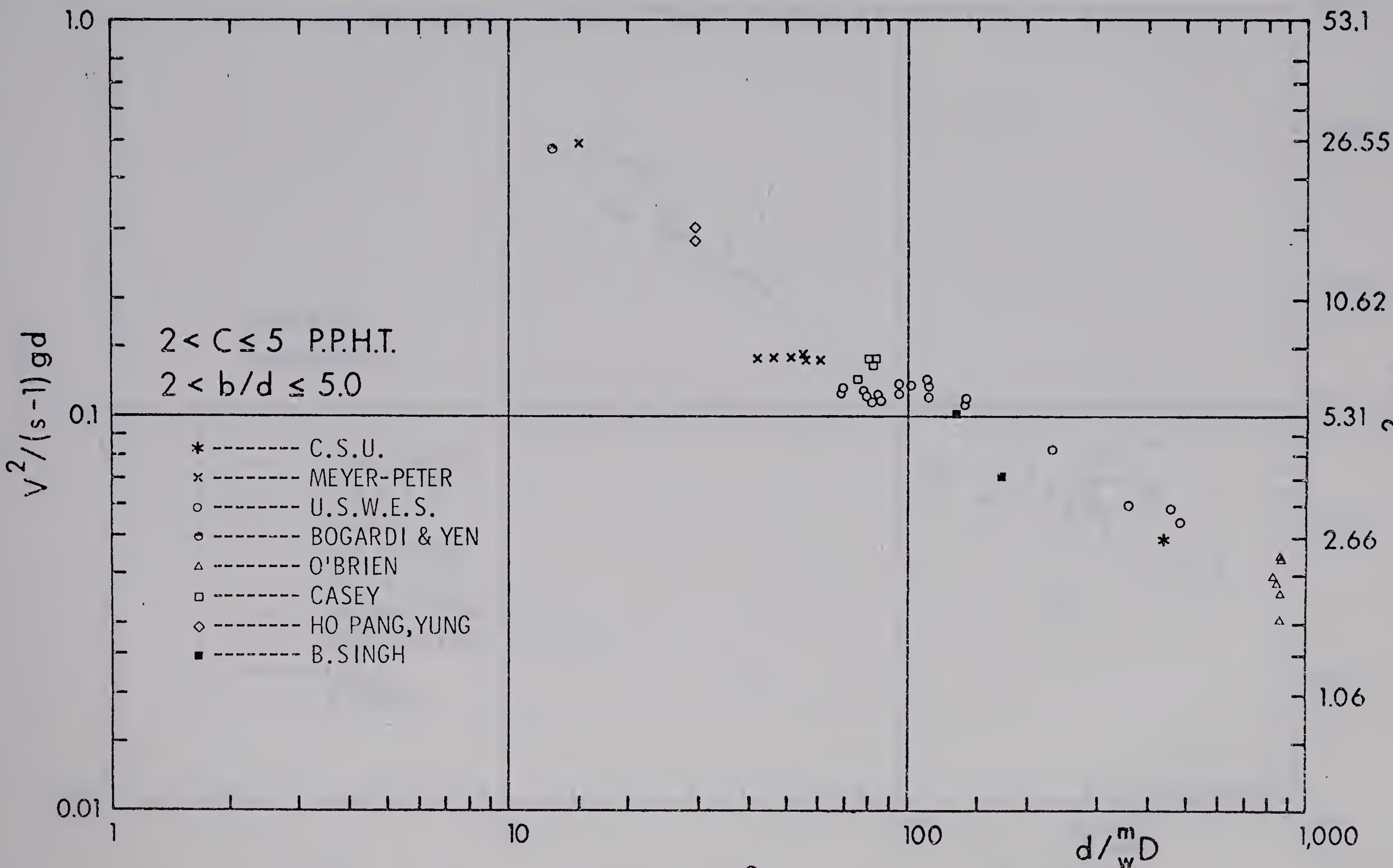



FIG. A-23 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$

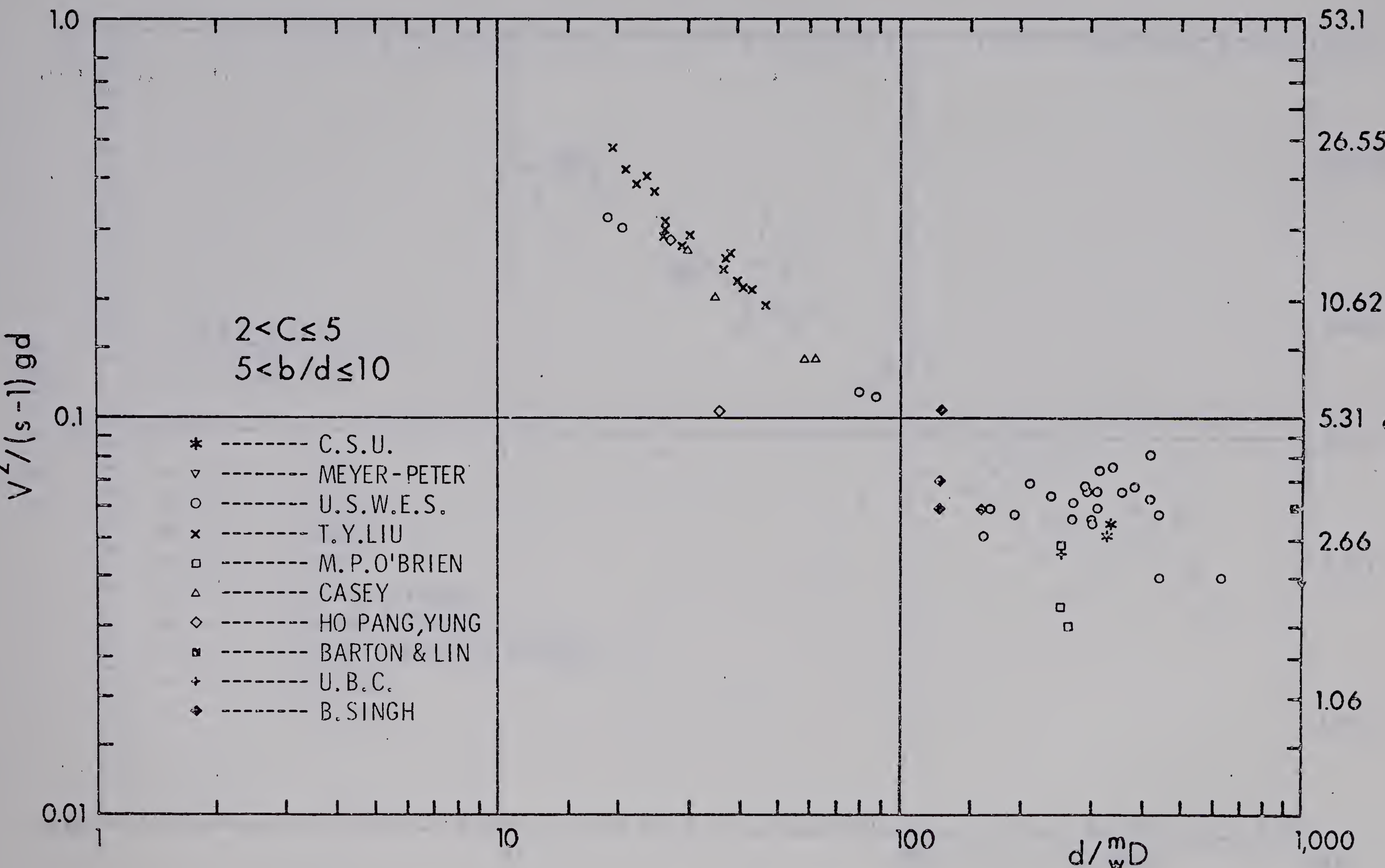



FIG. A-24 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$

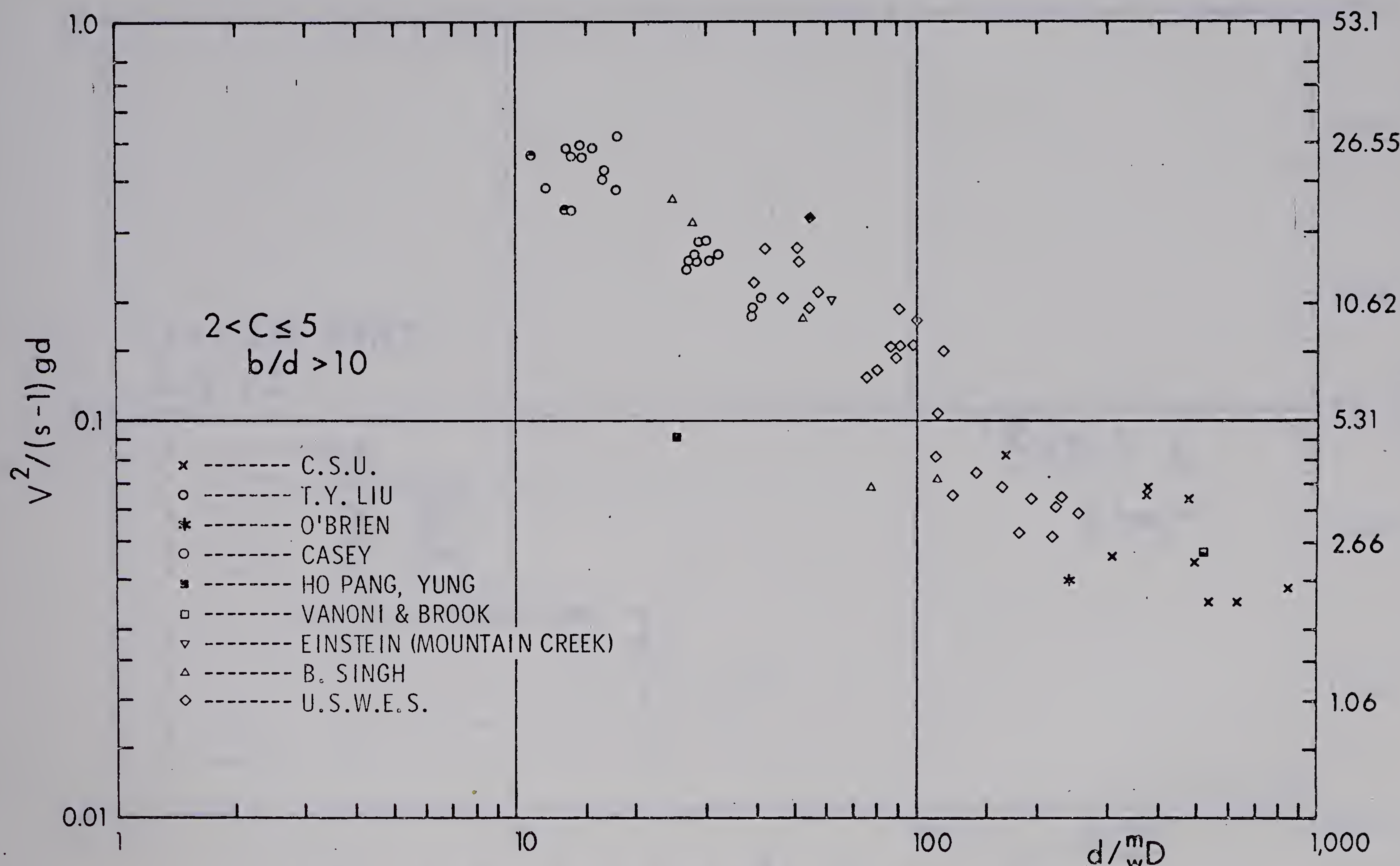



FIG. A-25 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^{m}_{w}D$

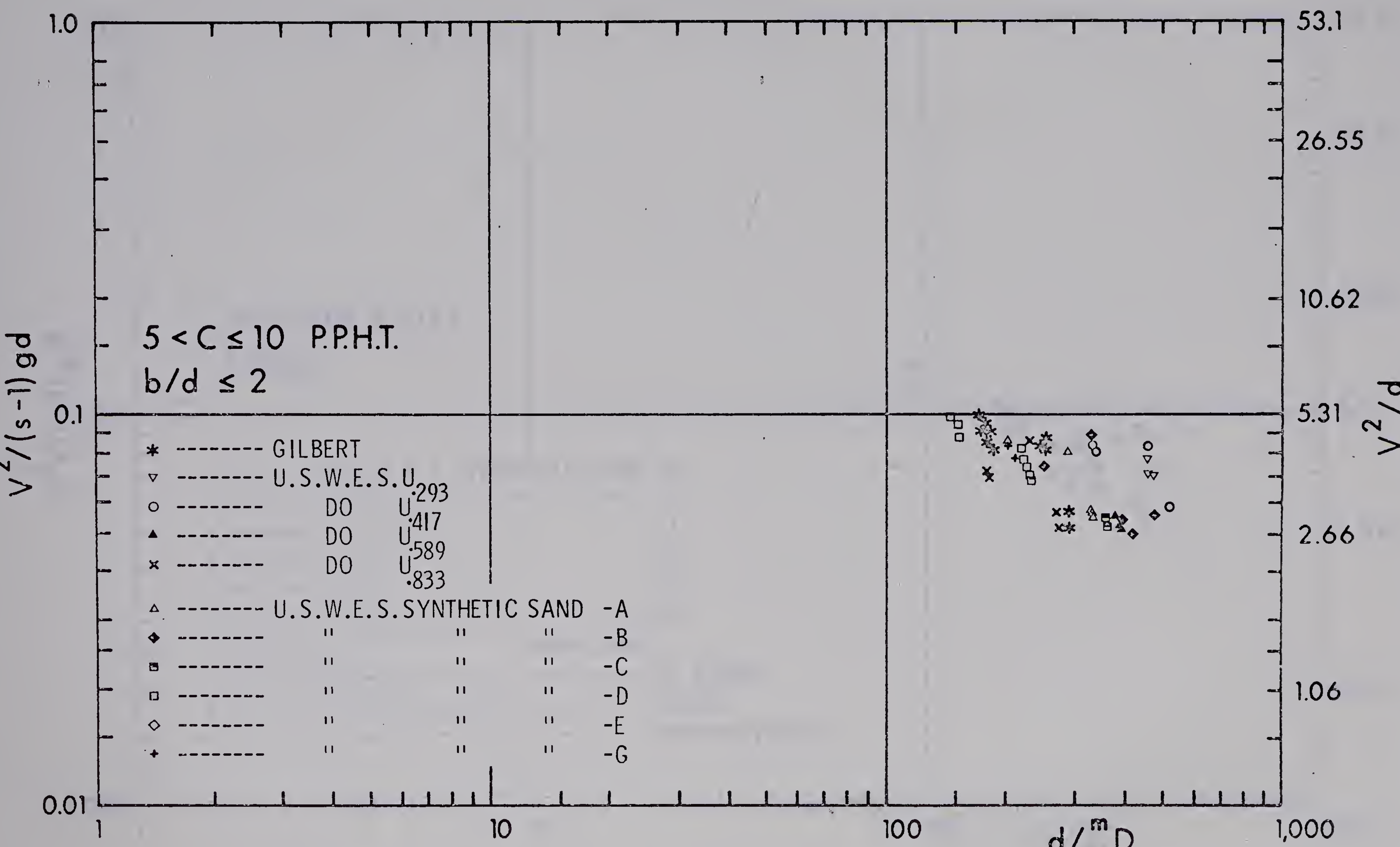
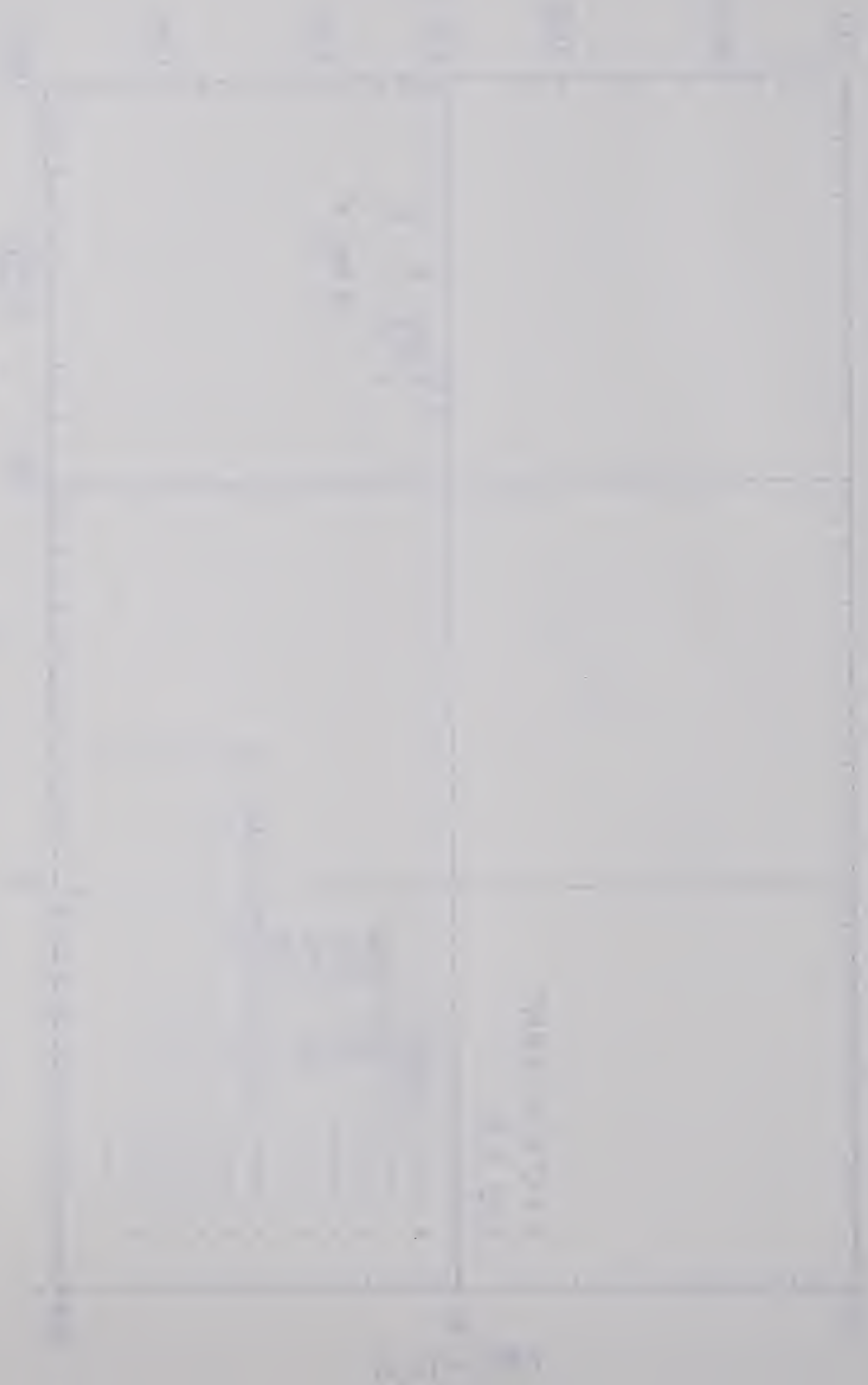



FIG. A-26 (a) PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$



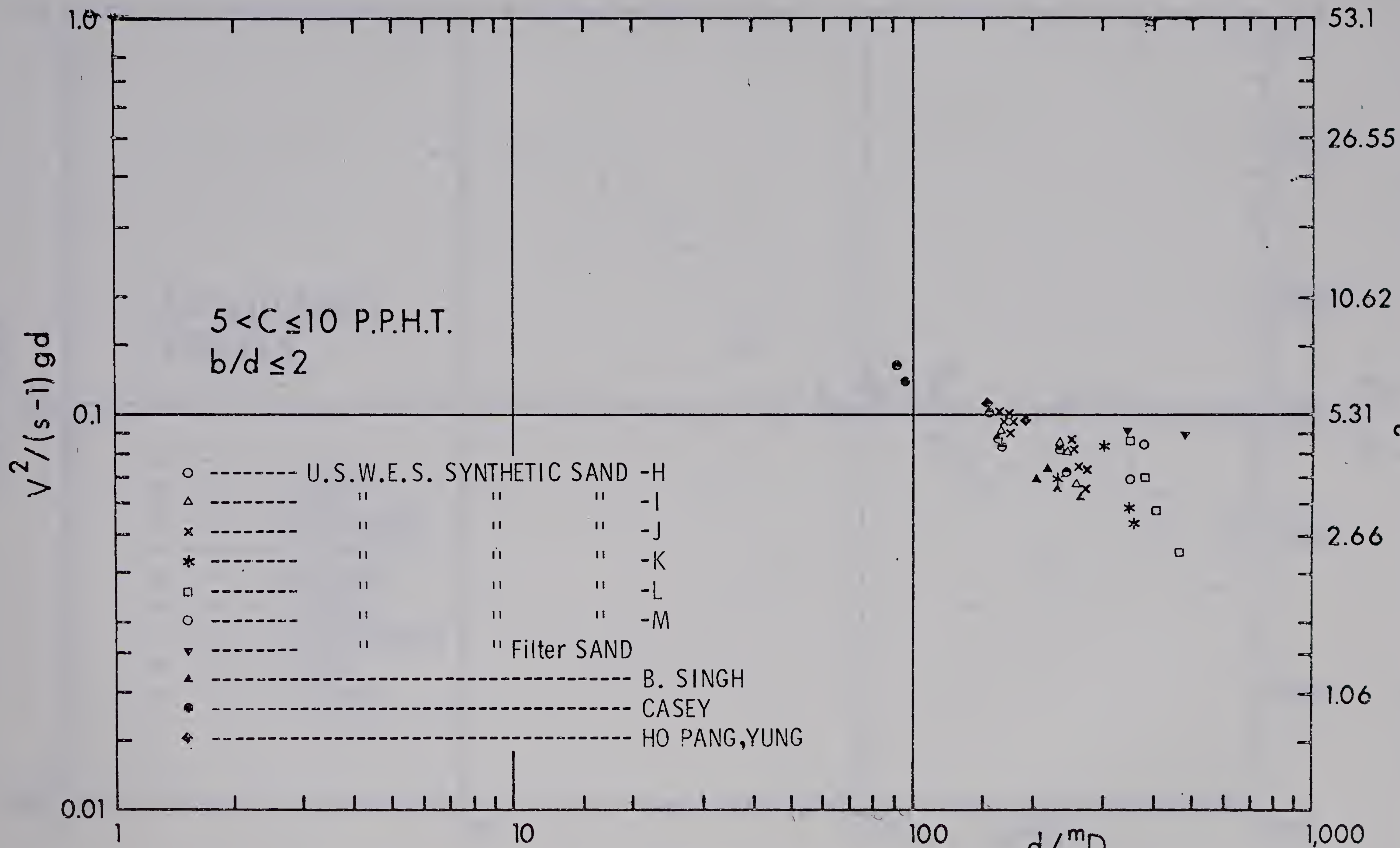



FIG. A-26(b) PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_wD$

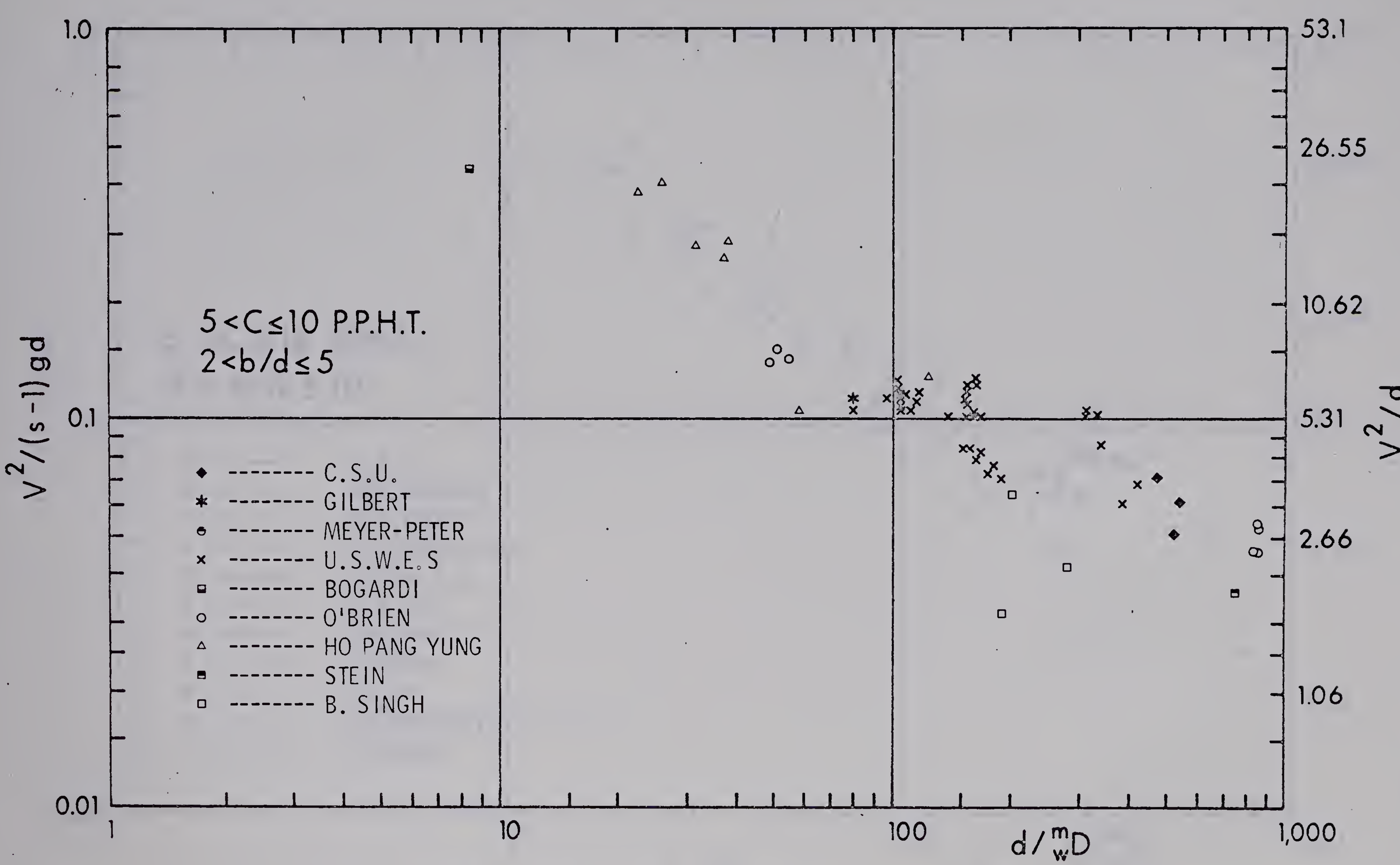



FIG. A-27 PLOT OF $V^2/(s-1)gd$ vs. $d/{}^m_w D$

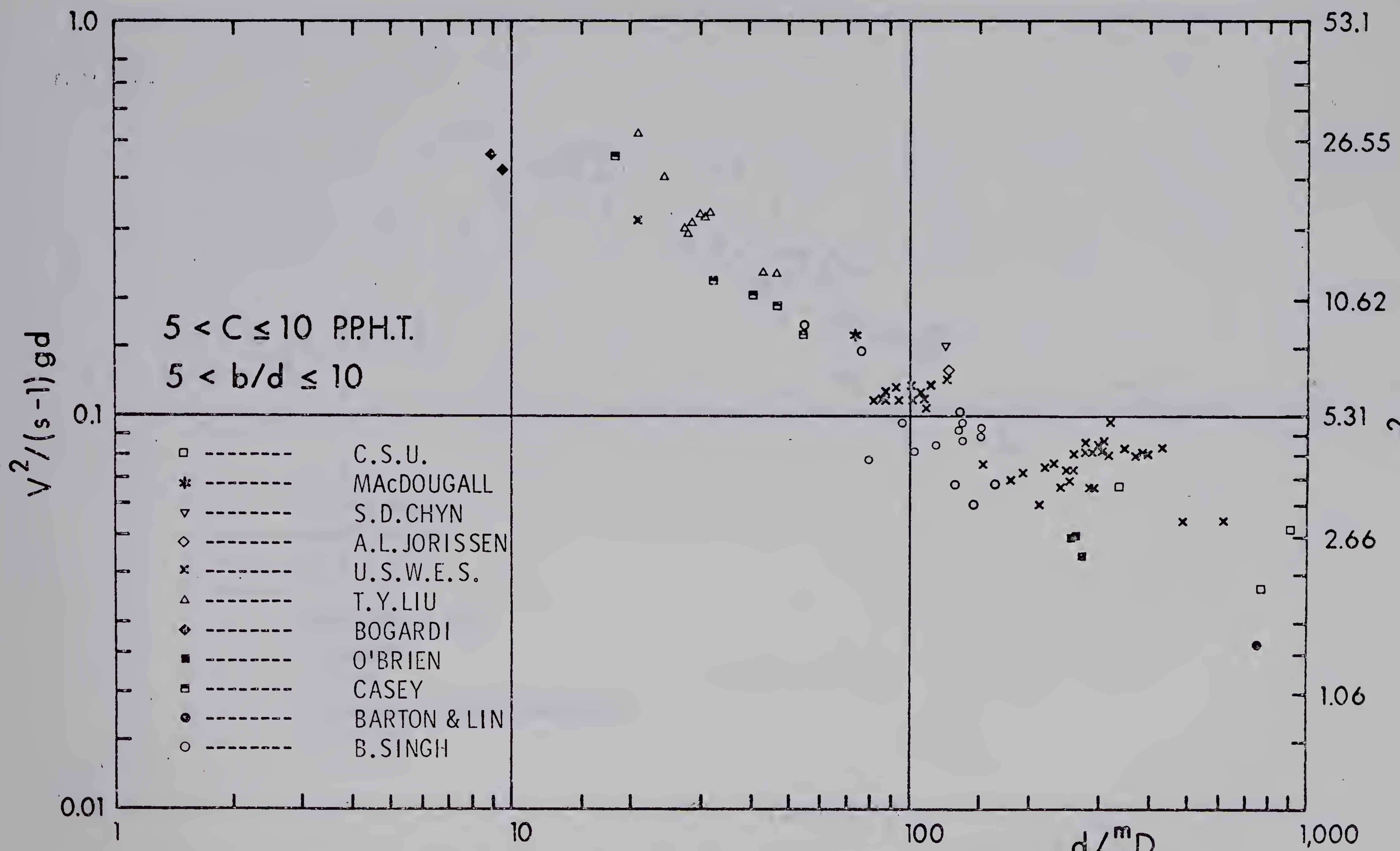



FIG. A-28 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^{m}_{w}D$

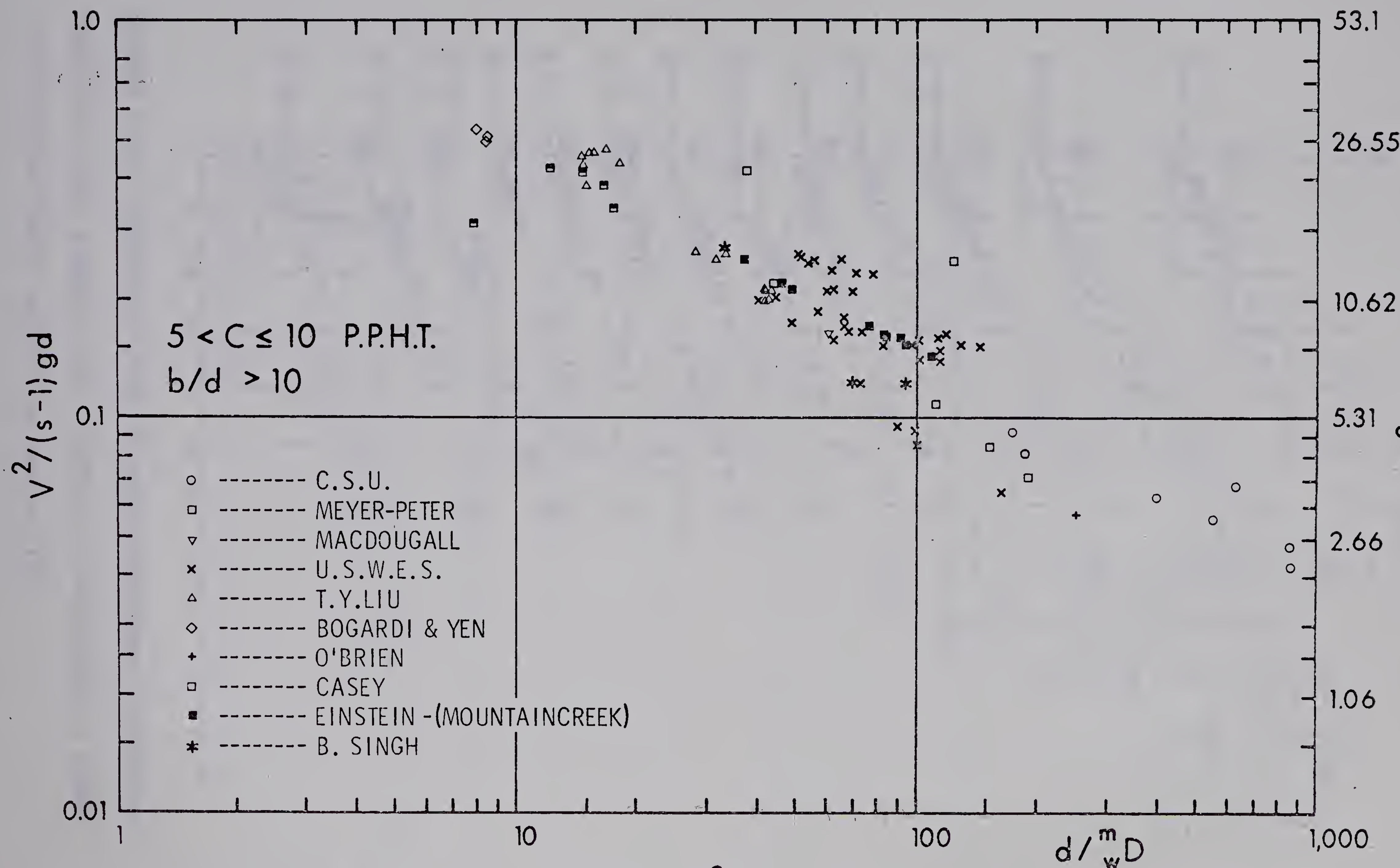



FIG. A-29 PLOT OF $V^2/(s-1)\,gd$ vs. $d/{}^m_wD$

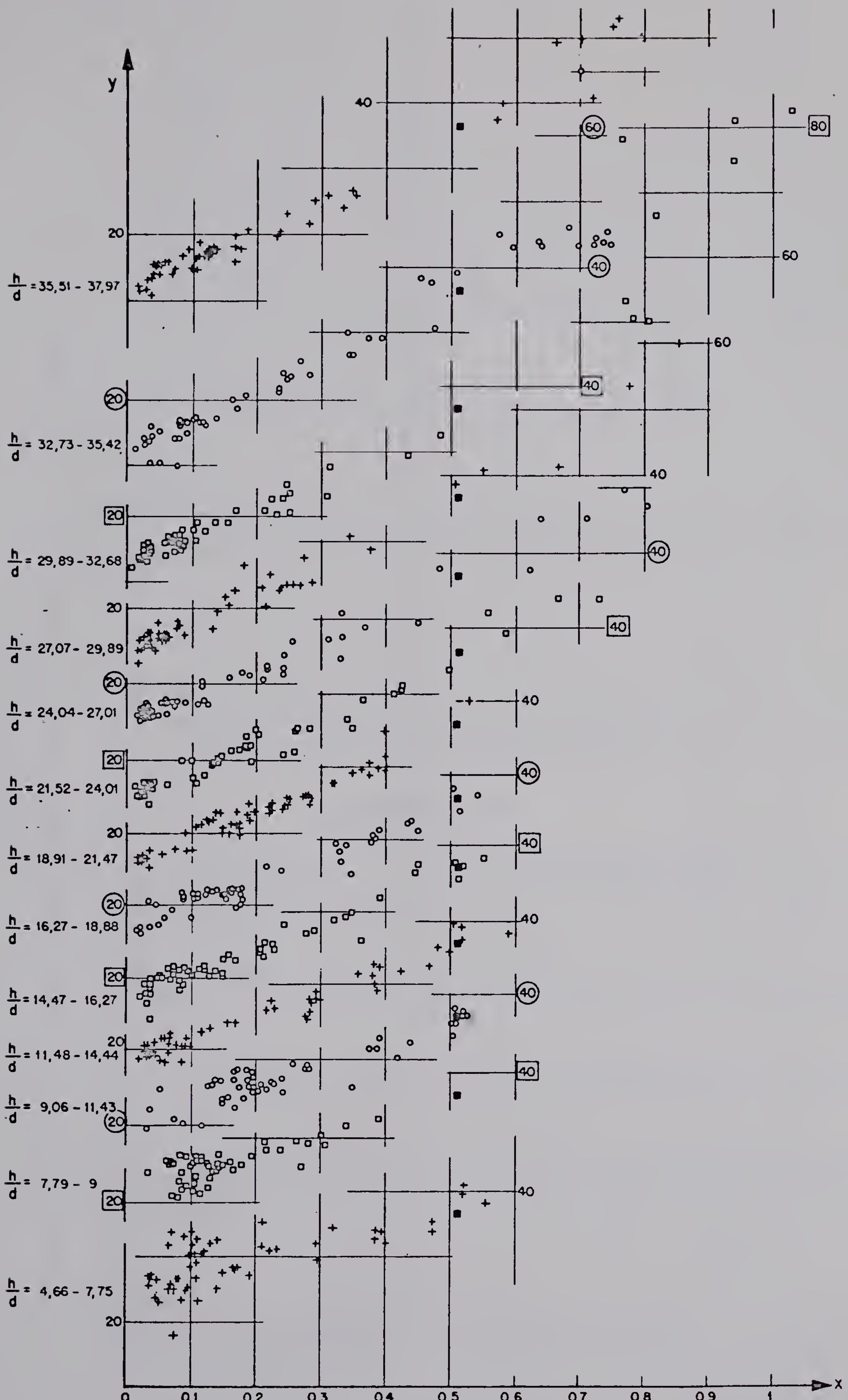



FIGURE A-30 ROTTNER'S PLOT OF NON-DIMENSIONAL TRANSPORT PARAMETERS FOR VARIOUS d/D. ROTTNER (REFERENCE 6) USED "h" FOR FLOW DEPTH AND "d" FOR GRAIN-SIZE.

APPENDIX "B"

TABLE B-1

SIZE DISTRIBUTION OF MATERIALS USED IN VARIOUS EXPERIMENTS FROM WHICH DATA HAVE BEEN USED IN THIS ANALYSIS

| Name of Authors | Designation of Material as used by the Authors | Percent finer by Weight all in mm. $D_{50}$ | $D_{98}$ | $D_{84}$ | $D_{16}$ | $D_2$ | $G_R=\frac{1}{2}\left[\frac{D_{84}}{D_{50}}+\frac{D_{50}}{D_{16}}\right]$ | $D_{98}/D_{50}$ | $D_{84}/D_{50}$ | $D_2/D_{50}$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| U.S.W.E.S. | Sand 1 | 0.420 | 2.25 | 0.73 | 0.205 | ~ | 1.89 | 5.36 | 1.74 | — | |
| | Sand 2 | 0.450 | 1.65 | 0.70 | 0.304 | 0.186 | 1.51 | 3.66 | 1.55 | 0.414 | |
| | Sand 3 | 0.476 | 1.20 | 0.64 | 0.34 | 0.21 | 1.37 | 2.53 | 1.34 | 0.44 | Fraser River Sand |
| | Sand 4 | 0.436 | 1.28 | 0.72 | 0.25 | 0.128 | 1.70 | 2.94 | 1.65 | 0.294 | |
| | Sand 5 | 0.400 | 1.20 | 0.67 | 0.256 | 0.165 | 1.62 | 3.00 | 1.67 | 0.412 | $D_{98}/D_{50}$ = 1.9 |
| | Sand 6 | 0.320 | 0.5 | 0.39 | 0.26 | 0.190 | 1.22 | 1.56 | 1.22 | 0.594 | |
| | Sand 7 | 0.288 | 0.6 | 0.398 | 0.198 | 0.115 | 1.42 | 2.08 | 1.38 | 0.40 | |
| | Sand 8 | 0.181 | 0.46 | 0.238 | 0.14 | 0.10 | 1.30 | 2.54 | 1.31 | 0.55 | |
| | Sand 9 | 4.10 | 5.8 | 5.2 | 2.7 | 1.2 | 1.40 | 1.41 | 1.27 | 0.29 | $D_{84}/D_{50}$ = 1.4 |
| | Sand 10 | 0.95 | 1.65 | 1.24 | 0.65 | 0.31 | 1.39 | 1.74 | 1.3 | 0.33 | |
| T. Y. Liu | I | 4.30 | 5.7 | 5.00 | 3.73 | 3.2 | 1.16 | 1.32 | 1.16 | 0.75 | $D_2/D_{50}$ = 0.52 |
| | II | 3.25 | 4.0 | 3.58 | 2.97 | 2.70 | 1.10 | 1.23 | 1.10 | 0.83 | |
| | III | 2.26 | 2.80 | 2.50 | 1.95 | 1.18 | 1.13 | 1.24 | 1.10 | 0.52 | |
| | IV | 1.48 | 1.90 | 1.68 | 1.14 | 0.49 | 1.22 | 1.28 | 1.13 | 0.33 | |
| | V | 3.60 | 5.2 | 4.58 | 3.14 | 2.80 | 1.21 | 1.44 | 1.27 | 0.78 | |
| | VI | 1.70 | 2.8 | 2.28 | 1.25 | 0.60 | 1.35 | 1.65 | 1.34 | 0.35 | |
| Colorado State University | 0.19 | 0.19 | 0.34 | 0.252 | 0.15 | 0.116 | 1.31 | 1.80 | 1.32 | 0.61 | |
| | 0.27 | 0.27 | 1.0 | 0.446 | 0.188 | 0.11 | 1.56 | 3.70 | 1.65 | 0.41 | |
| | 0.28 | 0.28 | $D_{97}$=2.4 | 0.50 | 0.190 | 0.12 | 1.67 | 8.5 | 1.78 | 0.43 | |
| | 0.45 | 0.45 | 1.18 | 0.71 | 0.275 | 0.155 | 1.60 | 2.62 | 1.58 | 0.34 | |
| | 0.47 | 0.47 | 1.18 | 0.73 | 0.296 | 0.175 | 1.54 | 2.50 | 1.55 | 0.37 | |
| | 0.54 | 0.54 | 1.32 | 0.80 | 0.345 | 0.21 | 1.52 | 2.44 | 1.48 | 0.39 | |
| | 0.93 | 0.93 | 1.85 | 1.34 | 0.58 | 0.265 | 1.54 | 2.0 | 1.44 | 0.29 | |
| | 0.32 | 0.32 | 1.09 | 0.52 | 0.213 | 0.155 | 1.57 | 3.42 | 1.62 | 0.49 | |
| | 0.33U | 0.33 | 0.54 | 0.42 | 0.26 | 0.144 | 1.25 | 1.64 | 1.27 | 0.47 | |
| | 0.33G | 0.33 | 1.09 | 0.64 | 0.154 | -- | 2.07 | 3.33 | 1.94 | -- | |
| B. Singh | - | 0.62 | 0.71 | 0.68 | 0.52 | -- | 1.13 | 1.14 | 1.1 | -- | |
| West Bengal River Research Institute | - | 0.31 | 0.44 | 0.362 | 0.235 | 0.165 | 1.25 | 1.42 | 1.17 | 0.53 | |
| H. J. Casey | h | 2.26 | - | 2.42 | 2.10 | -- | 1.07 | -- | 1.07 | -- | |
| | IIIa | 1.20 | - | 2.42 | 0.17 | -- | 4.53 | -- | 2.02 | -- | |
| Ho Pang Yung | I | 3.00 | 12.5 | 6.2 | 1.75 | -- | 1.88 | 4.17 | 2.07 | -- | |
| | II | 4.30 | 9.1 | 6.0 | 2.45 | 2.18 | 1.57 | 2.12 | 1.4 | 0.51 | |
| | III | 6.10 | 15.0 | 10.0 | 4.60 | 3.0 | 1.49 | 2.46 | 1.64 | 0.50 | |
| | IV | 1.30 | 4.0 | 2.1 | 0.72 | 0.5 | 1.71 | 3.08 | 1.61 | 0.38 | |
| | V | 6.00 | 8.5 | 7.45 | 4.4 | 2.9 | 1.30 | 1.42 | 1.24 | 0.48 | |
| | VI | 1.45 | - | 2.6 | 0.82 | 0.5 | 1.78 | -- | 1.8 | 0.35 | |
| H. A. Einstein | Mountain Creek Material | 0.90 | 3.05 | 1.61 | 0.50 | 0.265 | 1.84 | 3.40 | 1.8 | 0.30 | |

TABLE B-1 CONTINUED

| Name of Authors | Designation of Material as used by the Authors | Percent finer by Weight (all in mm.) $D_{50}$ | $D_{98}$ | $D_{84}$ | $D_{16}$ | $D_2$ | $G_R=\frac{1}{2}\left[\frac{D_{84}}{D_{50}}+\frac{D_{50}}{D_{16}}\right]$ | $D_{98}/D_{50}$ | $D_{84}/D_{50}$ | $D_2/D_{50}$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M. P. O'Brien | - | 0.360 | 0.88 | 0.55 | 0.25 | 0.17 | 1.48 | 2.44 | 1.53 | 0.47 | |
| Bogardi & Yen | 1 | 10.0 | 11.4 | 10.7 | 9.4 | 8.8 | 1.06 | 1.14 | 1.07 | 0.88 | Fraser River |
| | 3 | 15.0 | 16.3 | 15.6 | 14.4 | 13.8 | 1.04 | 1.09 | 1.04 | 0.92 | Sand |
| U.B.C. | 0.31 | 0.31 | - | 0.50 | 0.225 | 0.16 | 1.51 | -- | 1.61 | 0.51 | $D_{98}/D_{50}$ = 1.9 |
| | 0.197 | 0.197 | 0.55 | 0.278 | 0.134 | -- | 1.47 | 2.8 | 1.41 | -- | |
| Elbow River | 1 Sample 62 | 25 | 52 | 36 | 13 | -- | 1.68 | 2.08 | 1.44 | -- | |
| | 2 Sample 63 | 22 | - | 62 | - | -- | -- | -- | 2.80 | -- | |
| | 3 Sample 64 | 30.5 | 100 | 49 | 16 | -- | 1.75 | 3.3 | 1.6 | -- | $D_{84}/D_{50}$ = 1.4 |
| | 4 Sample 65 | 30.5 | 100 | 58 | 18 | 12 | 1.8 | 3.28 | 1.9 | 0.39 | |
| | 5 Sample 66 | 36 | 140 | 63 | 20 | 12 | 1.78 | 3.9 | 1.75 | 0.33 | |
| | 6 Sample 67 | 33 | 82 | 60 | 16 | -- | 1.94 | 2.5 | 1.80 | -- | $D_2/D_{50}$ = 0.52 |
| | 7 Sample 68 | 13 | 48 | 26 | - | -- | -- | 3.7 | 2.0 | -- | |
| MacDougall | II | 0.93 | 2.53 | 1.33 | 0.63 | 0.42 | 1.46 | 2.72 | 1.43 | 0.45 | |
| | U.589 | 0.67 | 0.84 | 0.745 | 0.60 | 0.48 | 1.10 | 1.25 | 1.10 | 0.72 | |
| | U.293 | 0.36 | 0.47 | 0.41 | 0.31 | 0.24 | 1.15 | 1.3 | 1.14 | 0.67 | |
| | U.833 | 0.94 | 1.18 | 1.04 | 0.84 | 0.75 | 1.11 | 1.26 | 1.10 | 0.80 | |
| | U.417 | 0.48 | 0.59 | 0.53 | 0.435 | 0.39 | 1.10 | 1.23 | 1.10 | 0.81 | |
| | A | 0.77 | 1.15 | 0.935 | 0.635 | 0.47 | 1.21 | 1.50 | 1.21 | 0.61 | |
| | B | 0.66 | 1.15 | 0.865 | 0.515 | 0.39 | 1.30 | 1.74 | 1.31 | 0.59 | |
| U.S.W.E.S Synthetic Mixture | D | 1.03 | 1.33 | 1.17 | 0.90 | 0.79 | 1.14 | 1.29 | 1.13 | 0.76 | |
| | E | 0.88 | 1.01 | 0.95 | 0.81 | 0.60 | 1.08 | 1.15 | 1.08 | 0.68 | |
| | F | 1.08 | 1.40 | 1.28 | 0.62 | 0.41 | 1.44 | 1.30 | 1.18 | 0.38 | |
| | G | 0.90 | 1.38 | 1.20 | 0.68 | 0.56 | 1.33 | 1.54 | 1.33 | 0.62 | |
| | H | 0.96 | 2.0 | 1.49 | 0.62 | 0.41 | 1.55 | 2.10 | 1.55 | 0.43 | |
| | I | 0.94 | 2.0 | 1.50 | 0.535 | 0.4 | 1.68 | 2.12 | 1.60 | 0.43 | |
| | J | 0.90 | 2.6 | 1.60 | 0.52 | 0.4 | 1.75 | 2.9 | 1.78 | 0.45 | |
| | K | 0.725 | 1.0 | 0.88 | 0.52 | 0.4 | 1.30 | 1.4 | 1.21 | 0.55 | |
| | L | 0.63 | 1.35 | 1.03 | 0.425 | 0.30 | 1.56 | 2.14 | 1.64 | 0.48 | |
| | M | 0.69 | 1.40 | 1.08 | 0.41 | 0.275 | 1.62 | 2.03 | 1.57 | 0.40 | |
| | Filter Sand | 0.45 | 2.0 | 0.87 | 0.265 | 0.185 | 1.81 | 4.4 | 1.93 | 0.41 | |
| S.K. Bhattacharya | 1.7 mm. | 1.7 | 2.15 | 2.0 | 1.2 | 0.72 | 1.30 | 1.27 | 1.18 | 0.43 | |
| M. A. Qureshi | 1.7 mm. | 1.7 | 2.15 | 2.0 | 1.2 | 0.72 | 1.30 | 1.27 | 1.18 | 0.43 | |
| A. L. Jorissen | I | 0.60 | 2.90 | 1.10 | 0.35 | 0.215 | 1.78 | 4.8 | 1.83 | 0.36 | |
| | II | 0.87 | - | 1.26 | 0.62 | 0.3 | 1.43 | -- | 1.45 | 0.34 | |
| S. D. Chyn | 3 | 0.58 | 2.65 | 1.56 | 0.28 | 0.2 | 2.38 | 4.5 | 2.7 | 0.35 | |
| R. A. Stein | - | 0.4 | - | 0.63 | 0.255 | -- | 1.57 | -- | 1.57 | -- | |
| Barton, J. R. & Lin, P.N. | - | 0.180 | 0.275 | 0.220 | 0.142 | 0.08 | 1.26 | 1.52 | 1.22 | 0.45 | |
| Vanoni & Brooks | IV | 0.143 | 0.18 | 0.160 | 0.128 | 0.11 | 1.16 | 1.26 | 1.12 | 0.77 | |

TABLE B-2 (a)

RANGE OF VALUES OF SOME IMPORTANT PARAMETERS* IN EXPERIMENTAL DATA USED IN THIS THESIS

* $b/d > 5$, C = 0 — 10.00 P.P.H.T.

| Name of Authors and Year of Publication or Experiment | D, Median Diameter of Material used in ft.x$10^3$ (mm.) | Q Cusec. | b/d | d/D | $V^2/d$ | $(\nu g)^{1/3} D/\nu$ | t °C | Bed Phase |
|---|---|---|---|---|---|---|---|---|
| U.S.W.E.S (1935) | 0.59 - 13.5 (0.18 - 4.1) | 0.11 - 2.2 | 5 - 50 | 17 - 645 | 2.0 - 18.0 | 4 - 90 | 15 - 27 | Not recorded. |
| T. Y. Liu (1937) | 5.5 - 14.0 (1.67 - 4.25) | 0.17 - 2.75 | 6 - 45 | 7.5 - 45 | 8 -30 | 35 - 110 | 22 - 30 | Not recorded. |
| Colorado State University (1956-'60) | 0.62 - 30.5 (0.19 - 0.93) | 1.85 - 16.0 | 6.5 - 27.5 | 160 -1700 | 0.59 - 4.9 | 3.6 - 21 | 9 - 22.5 | Plane bed to dunes mostly ripplies. |
| B. Singh (1960) | 2.034 (0.62) | 0.095 - 0.946 | 5.1 - 63 | 19.2 - 168.3 | 3.2 - 24.6 | 12.2 - 13.5 | 13.4 - 18.9 | Not recorded. |
| West Bengal River Research Institute (1963) | 1.010 (0.31) | 0.016 - 0.345 | 5.2 - 48 | 30 - 285 | 2.01 - 5.35 | 7.22 - 7.92 | 24 - 31 | Not recorded. |
| H. J. Casey (1935) | 3.93 & 7.4 (1.2 & 2.26) | 0.028 - 0.540 | 5.4 - 43.7 | 58.6 - 7.6 | 25.4 - 6.4 | 26.9 & 50.8 | Not recorded. | Not recorded. |
| Meyer Peter (1948) | 1.3 - 10.8 (0.4 - 3.3) | 0.51 - 14.1 | 5 - 35 | 38 - 1000 | 1.4 - 22 | 9 - 74 | Not recorded. | Not recorded. |
| M. A. Qureshi (1962) | 5.6 (1.70) | 1.95 - 2.47 | 5 - 7.3 | 72 - 103 | 2.62 - 70 | - | Not recorded. | Dune to Sheet-Flow. |
| O'Brien, M.P. (1936) | 1.181 (0.36) | 0.67 - 0.87 | 9.1 - 10.2 | 255 - 275 | 1.5 - 3.1 | 7 - 8 | 11 - 18 | Not recorded. |
| H. A. Einstein (1950) | 2.95 (0.9) | 2.7 - 8.0 | 56 - 180 | 37.3 - 110 | 7.9 - 12.0 | 20 - 21.4 | 20 - 25 | Not recorded. |
| Ho Pang Yung (1939) | 5 - 14 (1.52 - 4.3) | 0.12 - 0.68 | 5 - 11 | 17 - 35 | 5 -15 | 21 - 88 | 2 - 41 | Not recorded. |
| Bogardi and Yen (1938) | 32.8 (10.0) | 1.9 - 2.18 | 9 - 10 | 7.8 - 9.2 | 22 - 29 | 198 - 203 | 14 - 15 | Not recorded. |
| Elbow River Data (1967) | 100.0 (30.5) | 30.5 - 7.0 cfs. per ft. width | >>5 | 12 - 56 | 7.0 - 29 | - | - | - |

TABLE B-2 (a) CONTINUED

| Name of Authors and Year of Publication or Experiment | D, Median Diameter Material used in ft.x$10^3$ (mm.) | Q Cusec | b/d | d/D | $V^2/D$ | $(\nu g)^{1/3} D/\nu$ | t°C | Bed Phase |
|---|---|---|---|---|---|---|---|---|
| C. R. Neill (1966) | 16.4 - 34.8 (5.0 - 10.6) | - | 5 - 19 | 6 - 35.4 | 28.6 - 2.4 | - | ±20 | - |
| Mavis, Ho & Tu (1935) | 9.2 - 18.7 (2.5 - 5.7) | - | 3.5 - 10 | 21 - 60 | 4.7 - 3.2 | - | - | - |
| Linnton Hydraulics Lab. (1938) | 26 - 104 (7.9 - 31.7) | - | 4 - 5.8 | 17.5 - 40 | 11 - 21 | - | - | - |
| Meyer Peter & Muller (1948) | 6.1 - 28 (1.85 - 8.5) | - | 3.2 - 33 | 10 - 79 | 4.7 - 32 | - | - | - |

TABLE B-2 (b)

RANGE OF VALUES OF SOME IMPORTANT PARAMETERS * IN EXPERIMENTAL DATA USED IN THIS THESIS

* $b/d$ > OR < 5, C = 0.01 – 10.00 P.P.H.T.

| Name of Authors and Year of Publication or Experiment | D, Median Diameter of Materials used in ft.x$10^3$ (mm.) | Q Cusec. | b/d | d/D | $V^2/d$ | $(vg)^{1/3}D/\nu$ | $t^{o}C$ | Bed Phase |
|---|---|---|---|---|---|---|---|---|
| U.S.W.E.S (1935) | 0.59 - 13.5 (0.18 - 4.1) | 0.098 - 2.2 | 1.08 - 49.3 | 17 - 745 | 1.6 - 18 | 3.7 - 90 | 15 - 27 | Not recorded |
| T. Y. Liu (1937) | 4.85 - 14 (1.48 - 4.30) | 0.17 - 2.6 | 6 - 46 | 7.5 - 46 | 9 - 31 | 35 - 110 | 22.5 - 30 | Not recorded |
| West Bengal (1963) | 1.01 (0.31) | 0.016 - 0.76 | 2.8 - 48 | 30 - 518 | 1.73 - 5.3 | 7.2 - 7.9 | 24 - 31 | Not recorded |
| B. Singh (1960) | 2.034 (0.62) | 0.095 - 0.946 | 1.5 - 6.3 | 19 - 270 | 3.1 - 24.5 | 12 - 13 | 13.5 - 19 | Not recorded |
| Colorado S.U. (1956-60) | 0.62 - 3.05 (0.19 - 0.93) | 0.88 - 15 | 3.2 - 27 | 160 - 1700 | 0.58 - 4.9 | 3.6 - 21 | 9 - 27 | Plane bed to Dunes |
| H. J. Casey (1935) | 3.937 & 7.415 (1.20 & 2.26) | 0.059 - 2.04 | 1.8 - 43 | 8 - 96 | 5.6 - 25.4 | 26.98 & 50.82 | Not recorded. | Not recorded |
| Meyer-Peter (1948) | 1.31 - 94 (0.4 - 28.6) | 0.54 - 162 | 1.4 - 35 | 15 - 1000 | 1.41 - 26.6 | 9 - 644 | Not recorded. | Not recorded |
| M. A. Qureshi (1962) | 5.6 (1.70) | 1.95 - 5.52 | 1.95 - 7.3 | 72 - 268 | 1.05 - 7.0 | - | Not recorded. | Dune to sheet -flow |
| M. P. O'Brien (1936) | 1.181 (0.36) | 0.67 - 0.87 | 9.3 - 10.3 | 250 - 275 | 1.55 - 3.10 | 7 - 8 | 15 - 18 | Not recorded |
| H. A. Einstein (1950) | 2.95 (0.9) | 2.7 - 8.0 | 47 - 180 | 37 - 110 | 8 - 13.75 | 20 - 21 | 20 - 25 | Not recorded |
| Ho Pang Yung (1939) | 4.2 - 20 (1.3 - 6.10) | 0.12 - 2.4 | 1.5 - 11 | 16 - 190 | 4.92 - 22 | 22 - 126 | 5.5 - 41 | Not recorded |
| Bogardi & Yen (1938) | 32.8 & 49.2 (10.0 & 15.0) | 0.70 - 2.33 | 1.55 - 10.7 | 8.2 - 13.1 | 20.2 - 31.2 | 200 - 340 | 14 - 22 | Not recorded |
| S. K. Bhattacharya (1960) | 5.6 (1.70) | 0.32 - 1.42 | 1.09 - 4 | 46 - 164 | 2.57 - 6.55 | - | Not recorded. | Just active to $F_{bo}$ - condition |
| Gilbert (1914) | 1.23 - 5.6 (0.38 - 1.7) | 0.363 - 0.734 | 1.3 - 3.1 | 55 - 600 | 1.23 - 6.0 | 8 - 38 | Not recorded. | Dunes |
| U.B.C. | 0.64 - 1.8 (0.2 - 0.55) | 0.174 - 0.63 | 1.8 - 8.4 | 180 - 588 | 1.21 - 2.5 | 4.3 - 13 | 5 - 21 | Not recorded. |

APPENDIX "C"

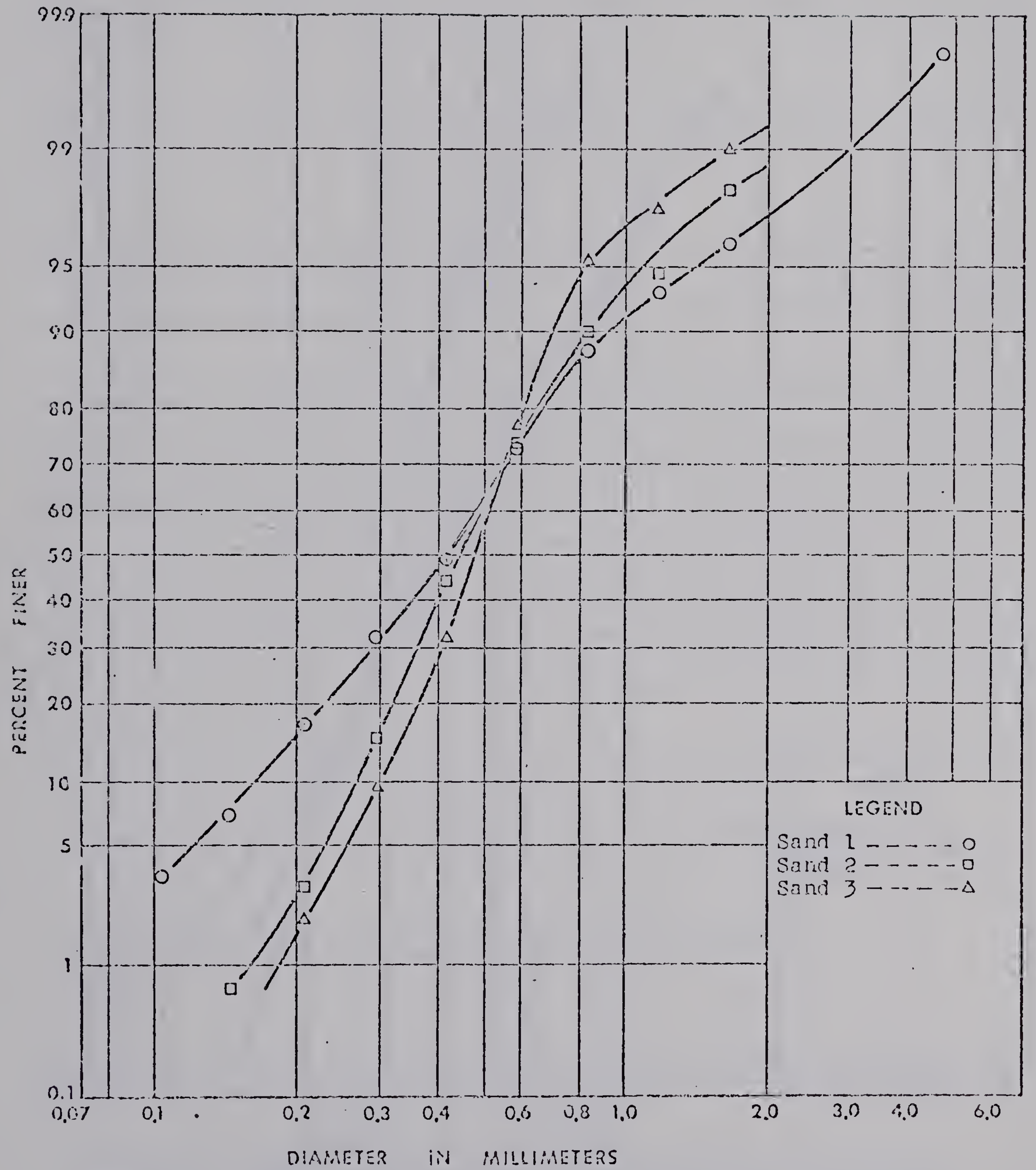



FIGURE C-1 - GRAIN SIZE DISTRIBUTION CURVES FOR U.S.W.E.S SAND NO. 1, 2, 3

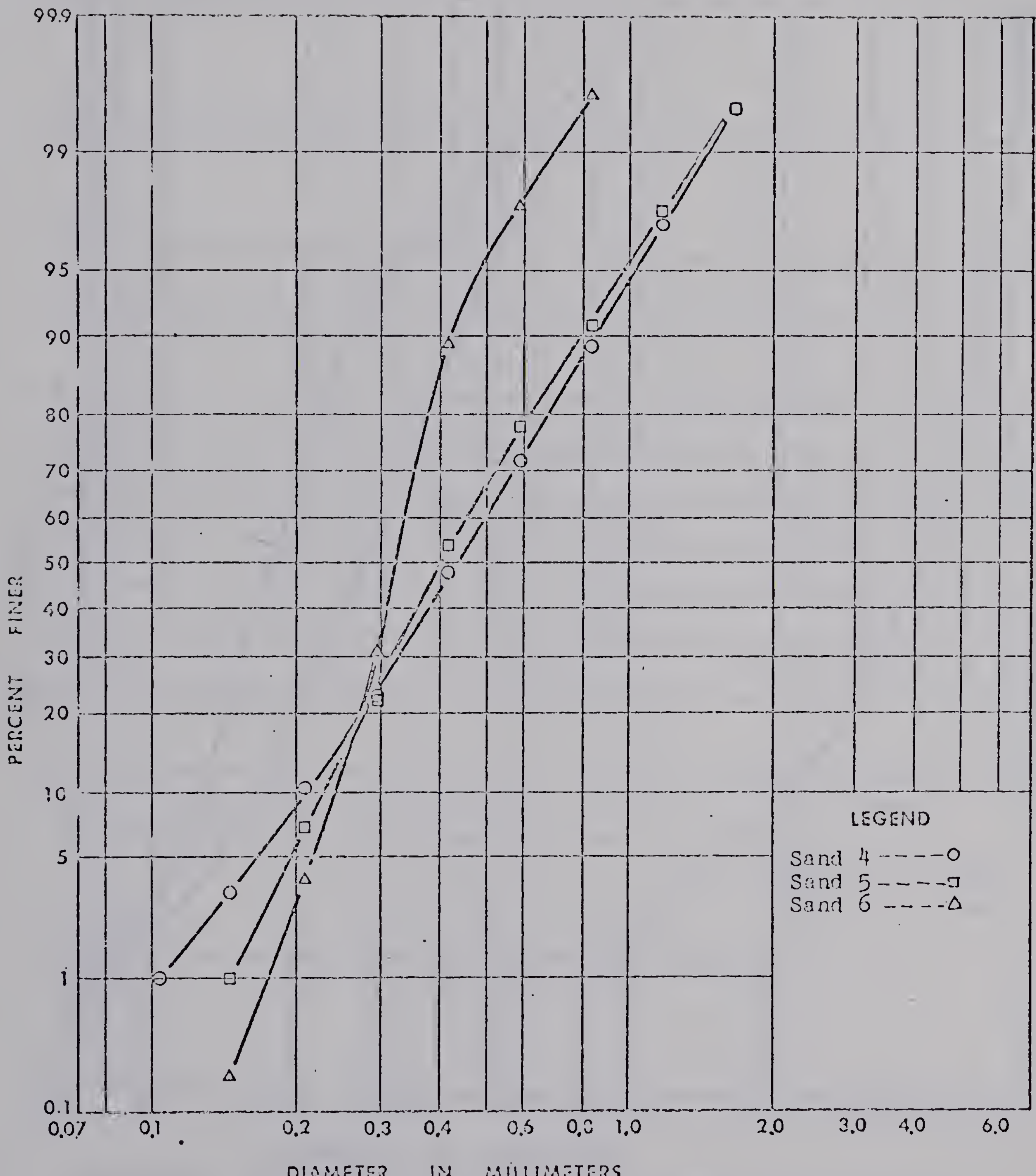



FIGURE C-2 - GRAIN SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SAND NO. 4, 5, 6

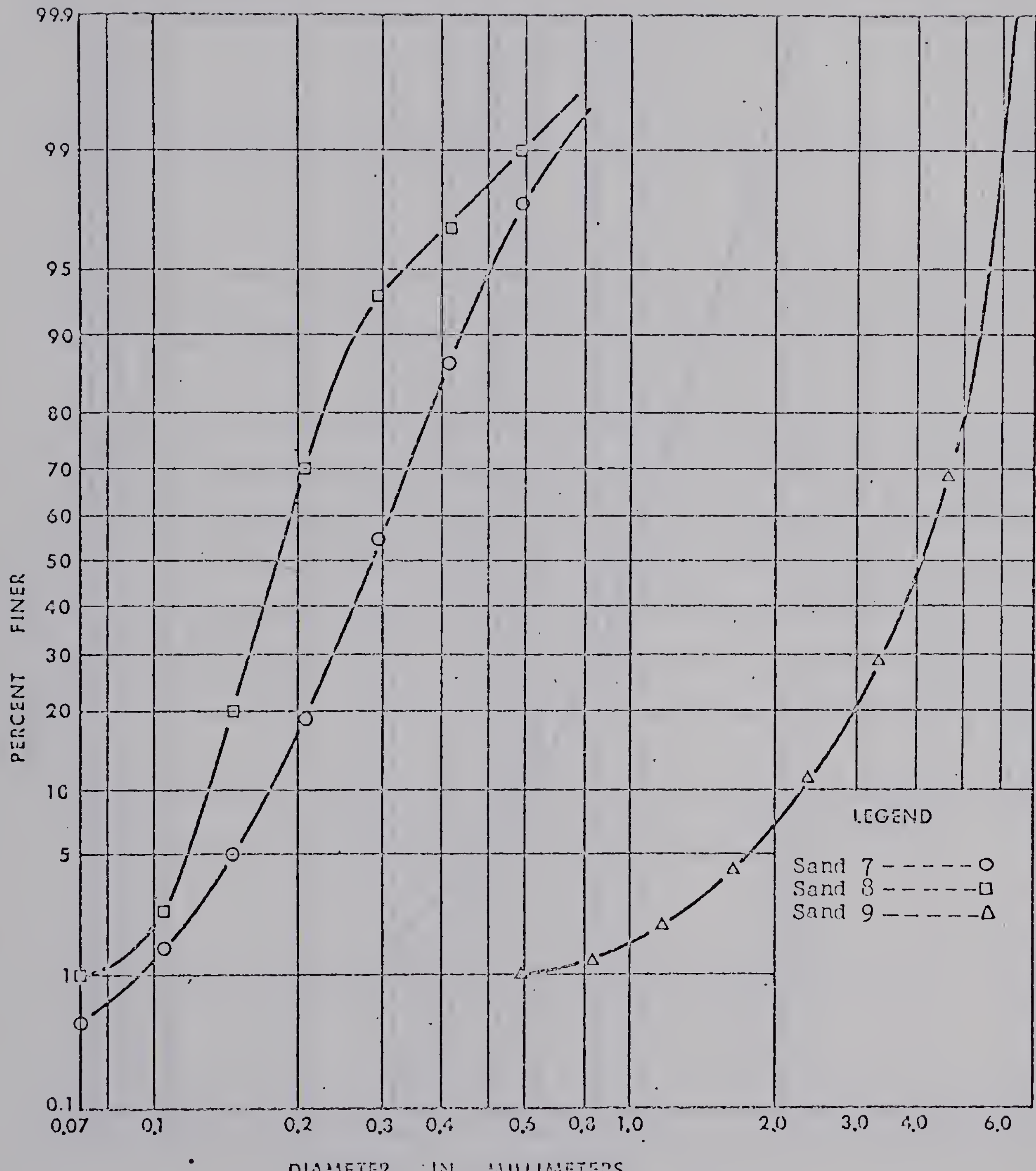



FIGURE C-3 - GRAIN-SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SAND NO. 7, 8, 9

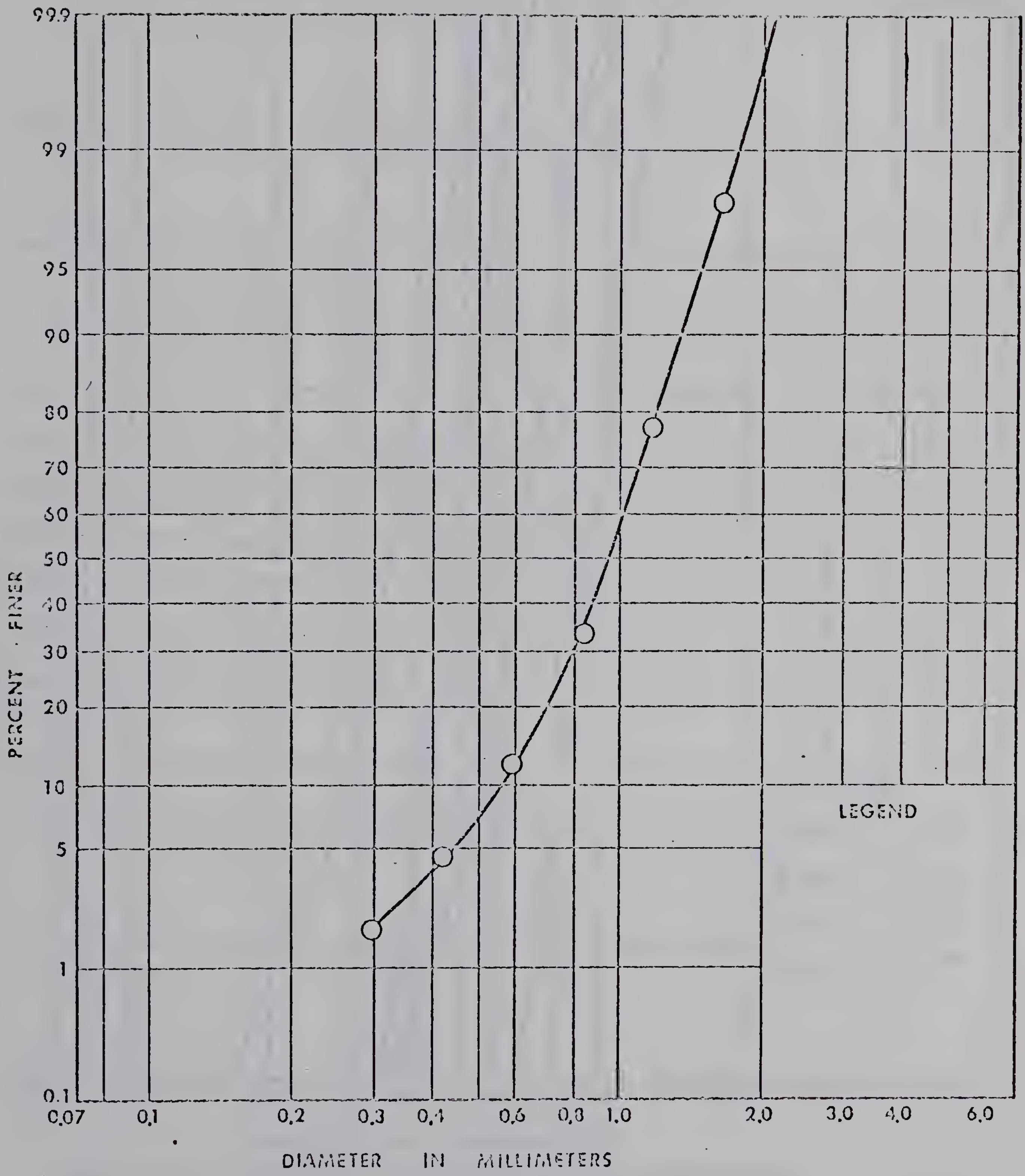



FIGURE C-4 - GRAIN-SIZE DISTRIBUTION CURVE FOR U.S.W.E.S.
SAND NO. 10

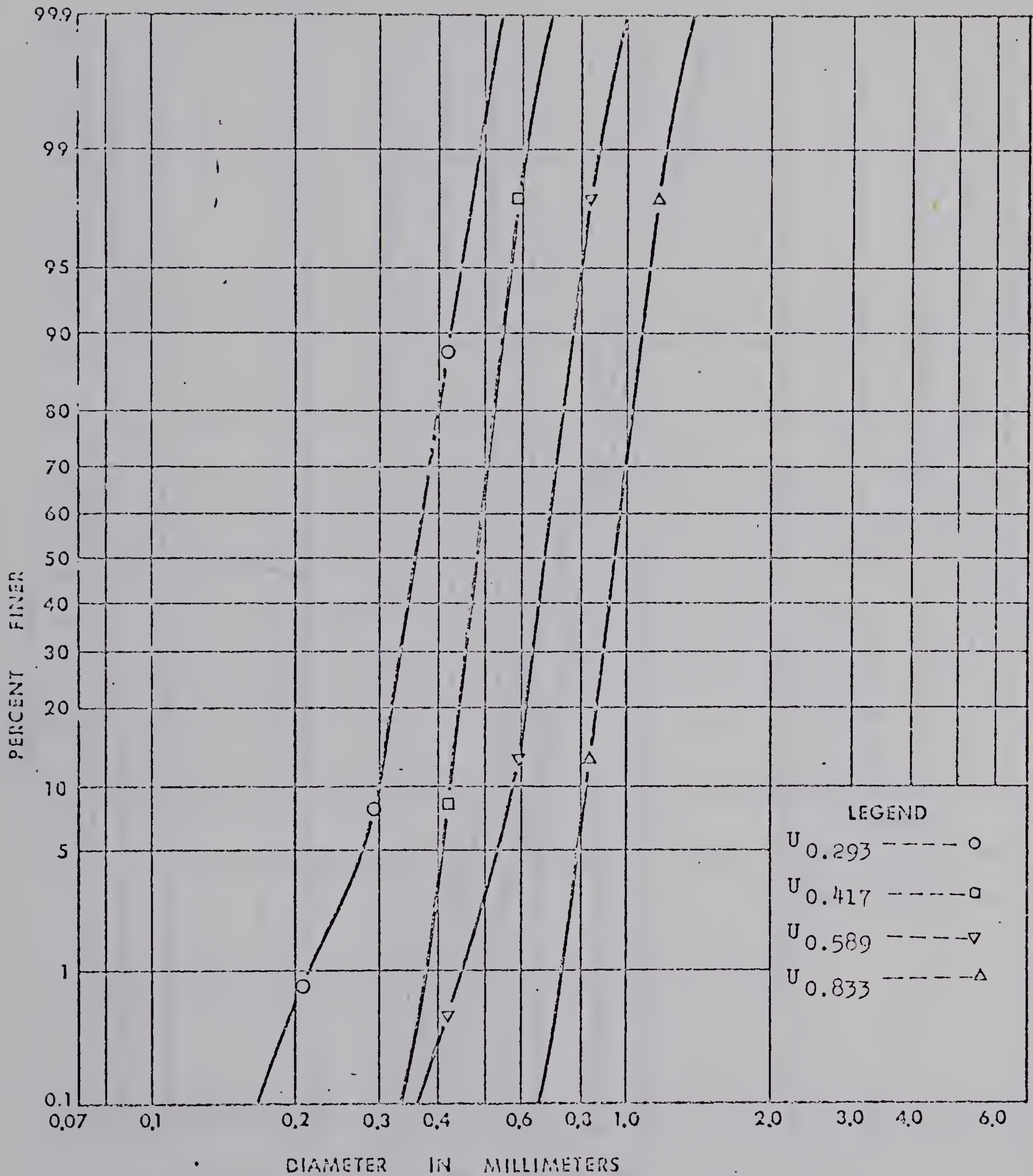



FIGURE C-5 - GRAIN-SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SYNTHETIC SAND $U_{0.293}$, $U_{0.417}$, $U_{0.589}$, $U_{0.833}$

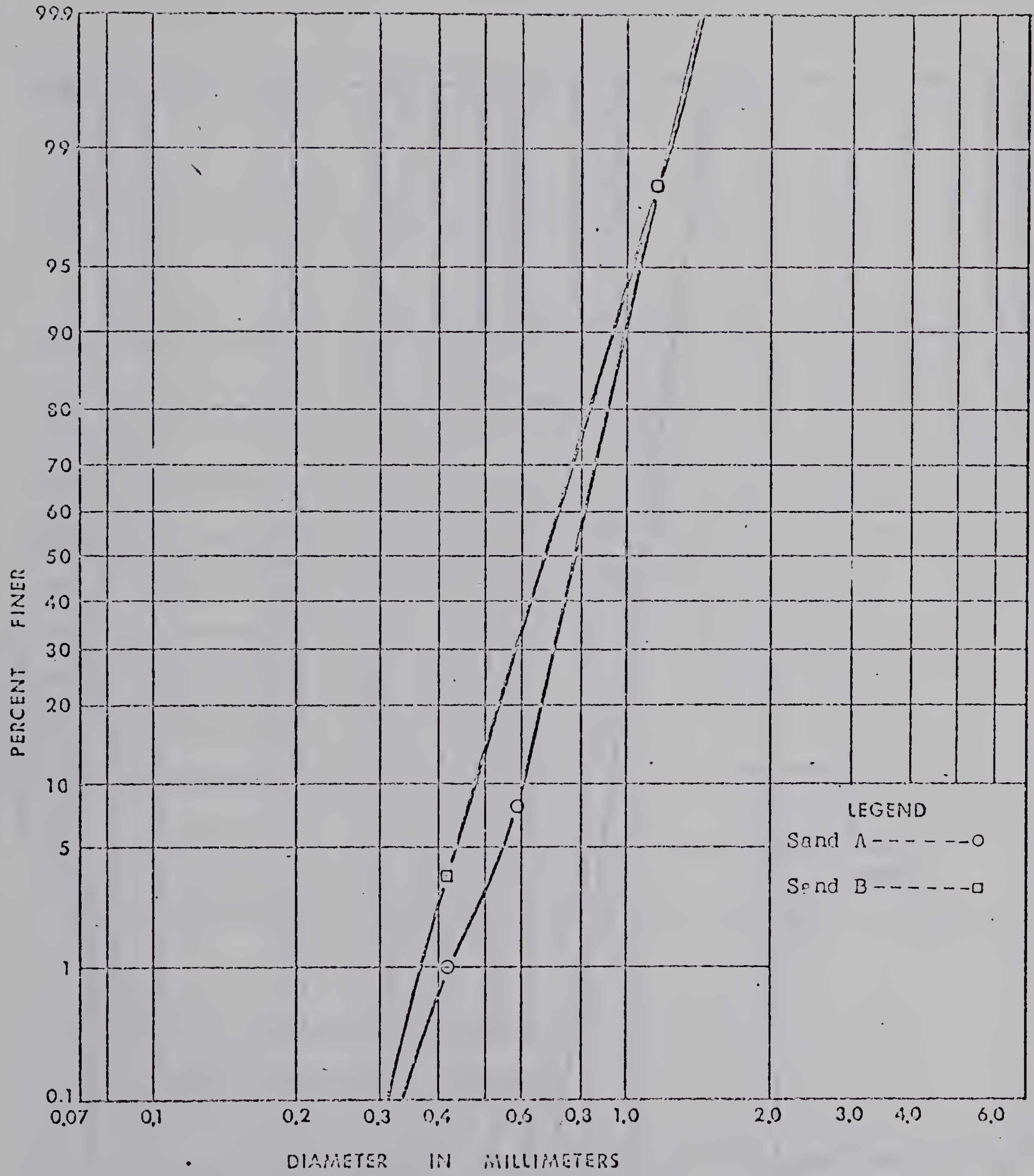



FIGURE C-6 - GRAIN-SIZE DISTRIBUTION CURVES FOR U.S.W.E.S SYNTHETIC SANDS A & B

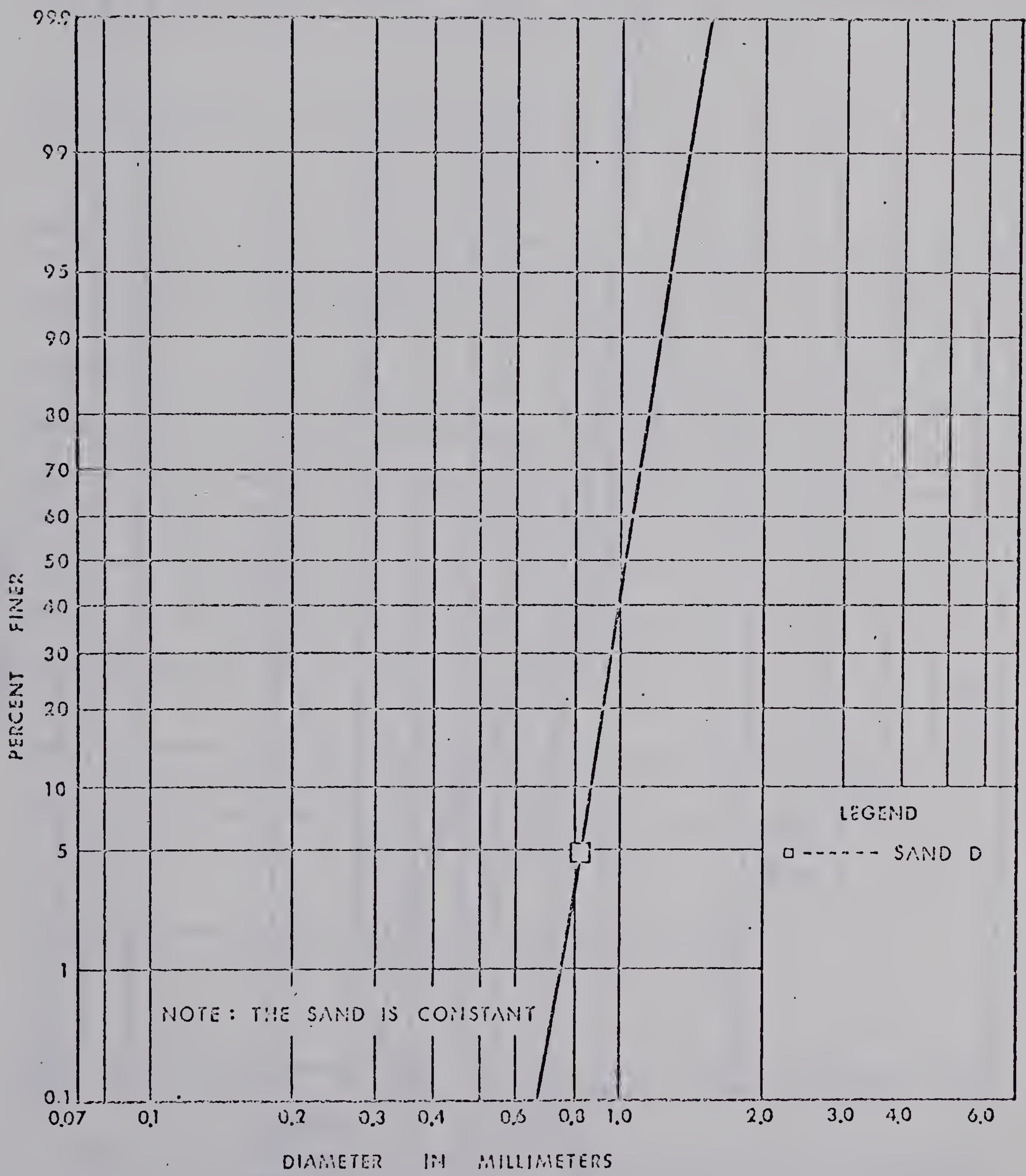



FIGURE C-7 - GRAIN-SIZE DISTRIBUTION CURVE FOR U.S.W.E.S. SYNTHETIC SAND D

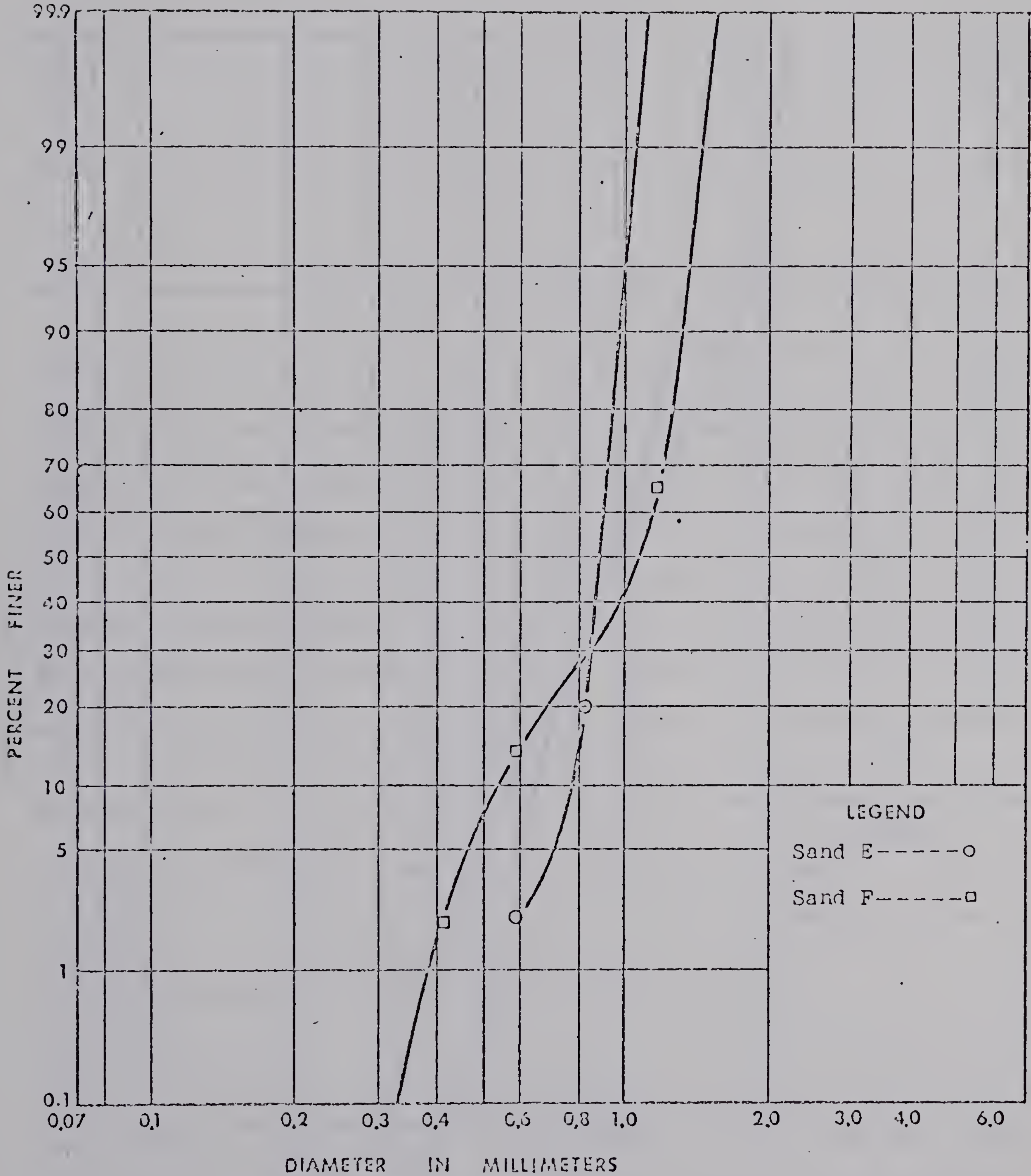



FIGURE C-8 - GRAIN-SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SYNTHETIC SANDS E & F

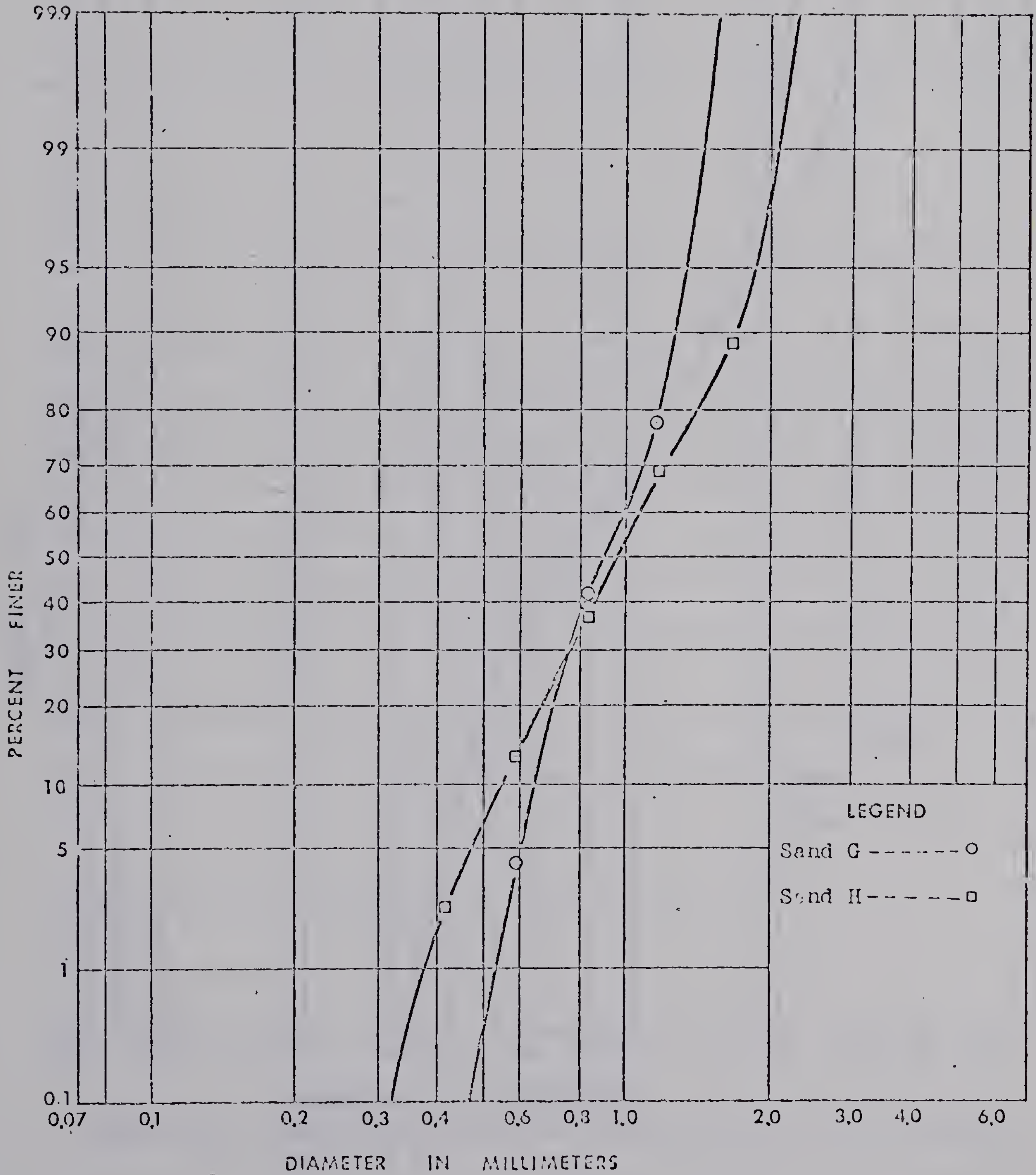



FIGURE C-9 - GRAIN-SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SYNTHETIC SANDS G & H

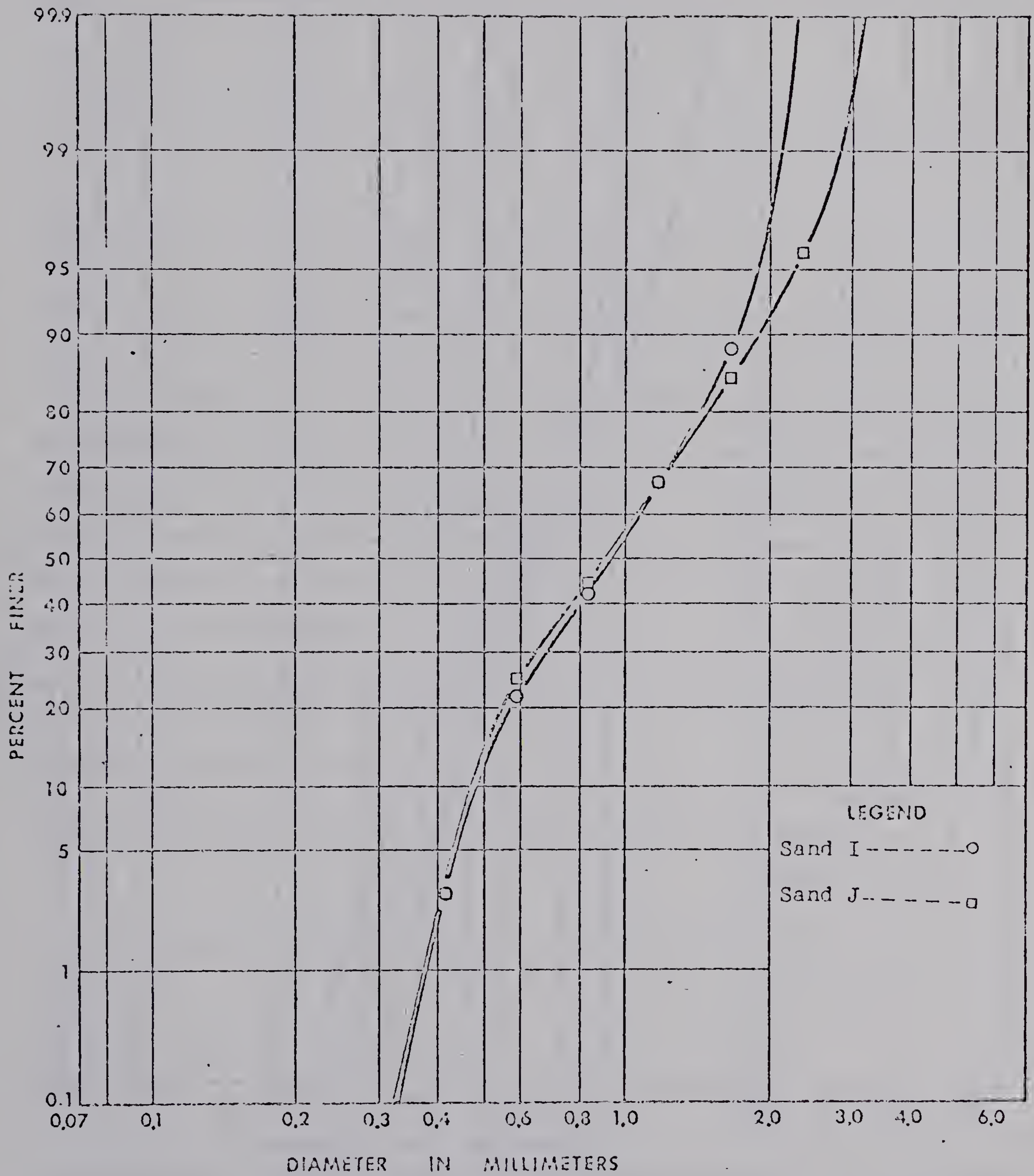



FIGURE C-10 - GRAIN-SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SYNTHETIC SANDS I & J

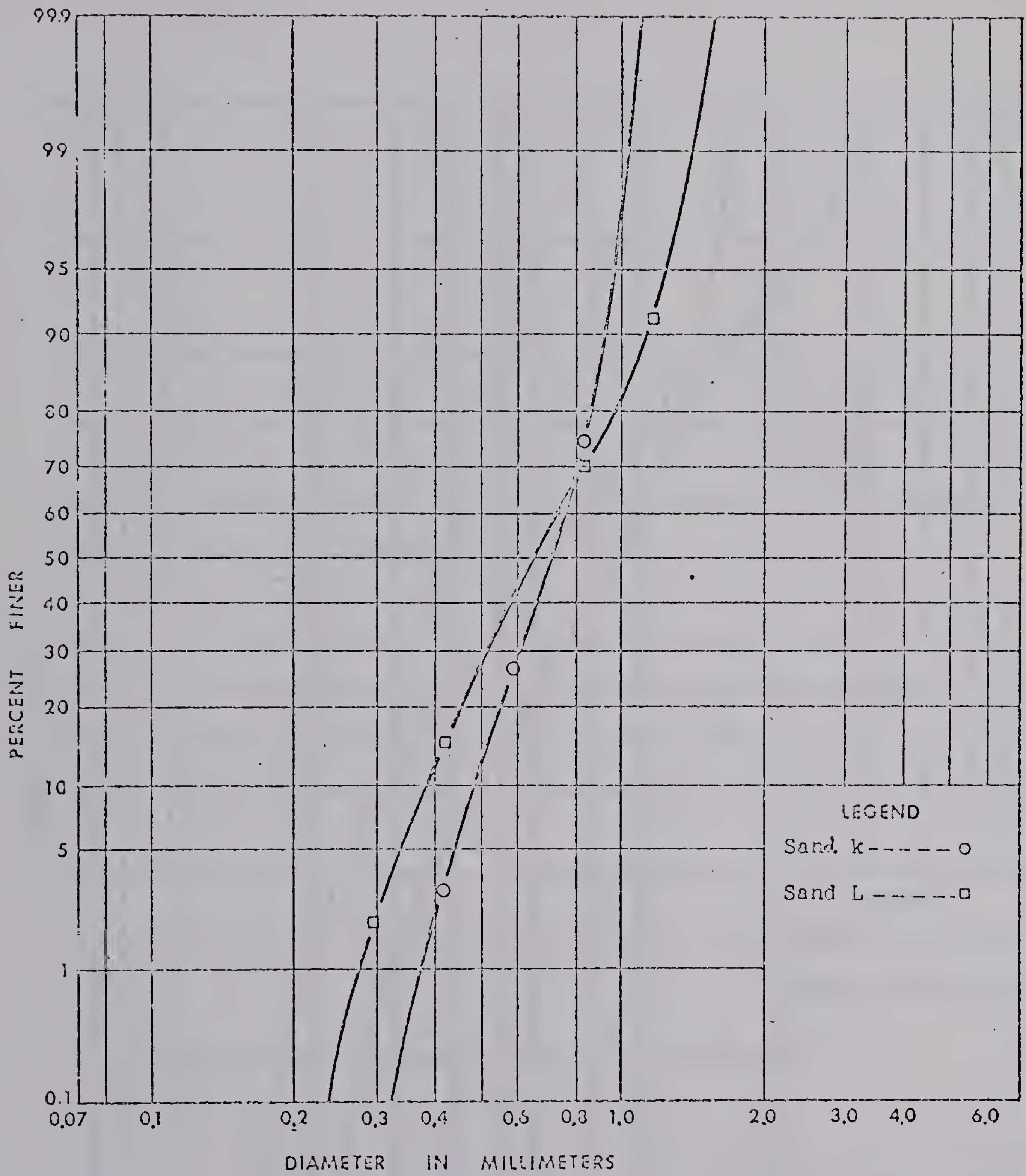



FIGURE C-11 - GRAIN SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SYNTHETIC SANDS K & L

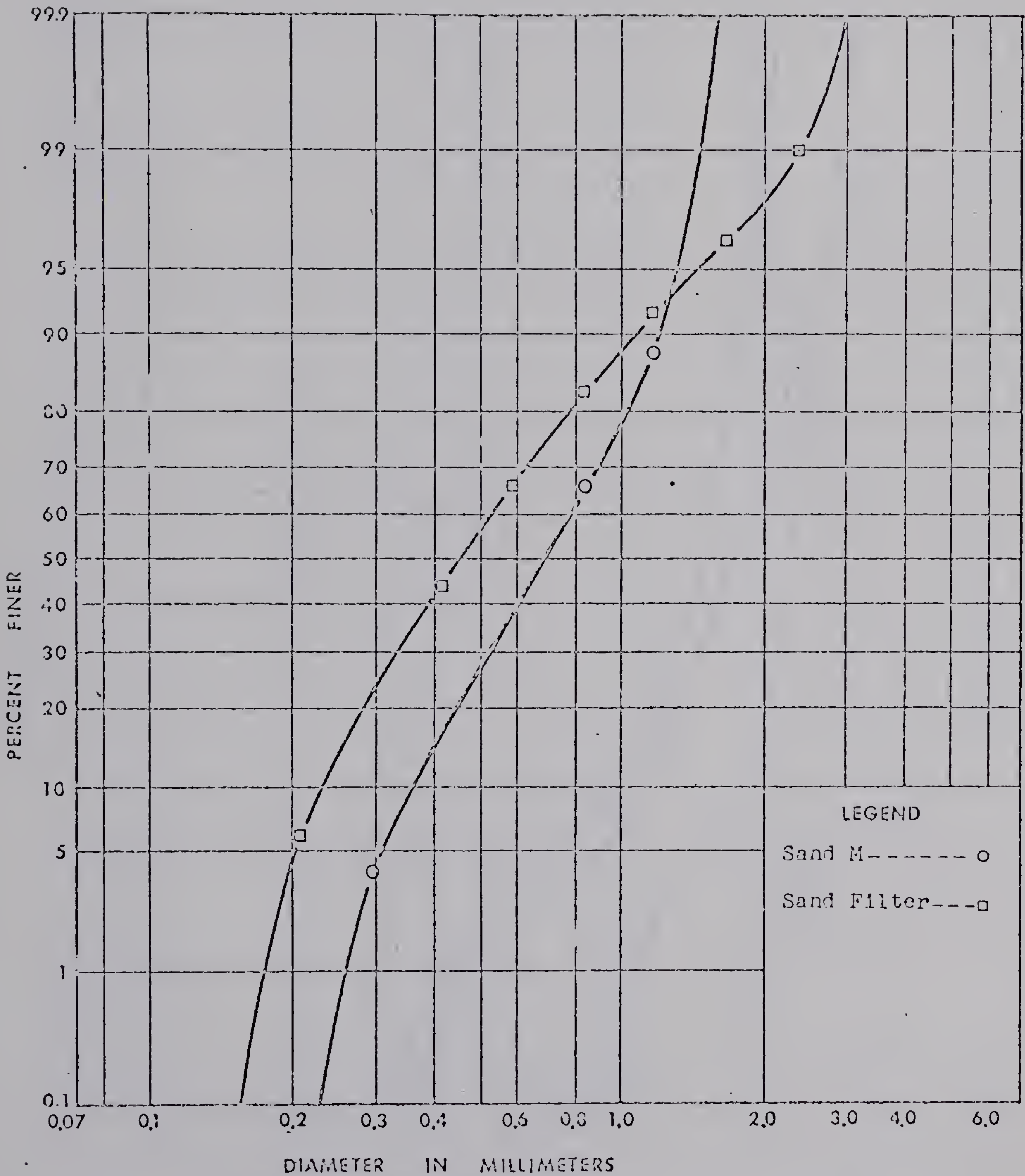



FIGURE C-12 - GRAIN SIZE DISTRIBUTION CURVES FOR U.S.W.E.S. SYNTHETIC SANDS M & FILTER

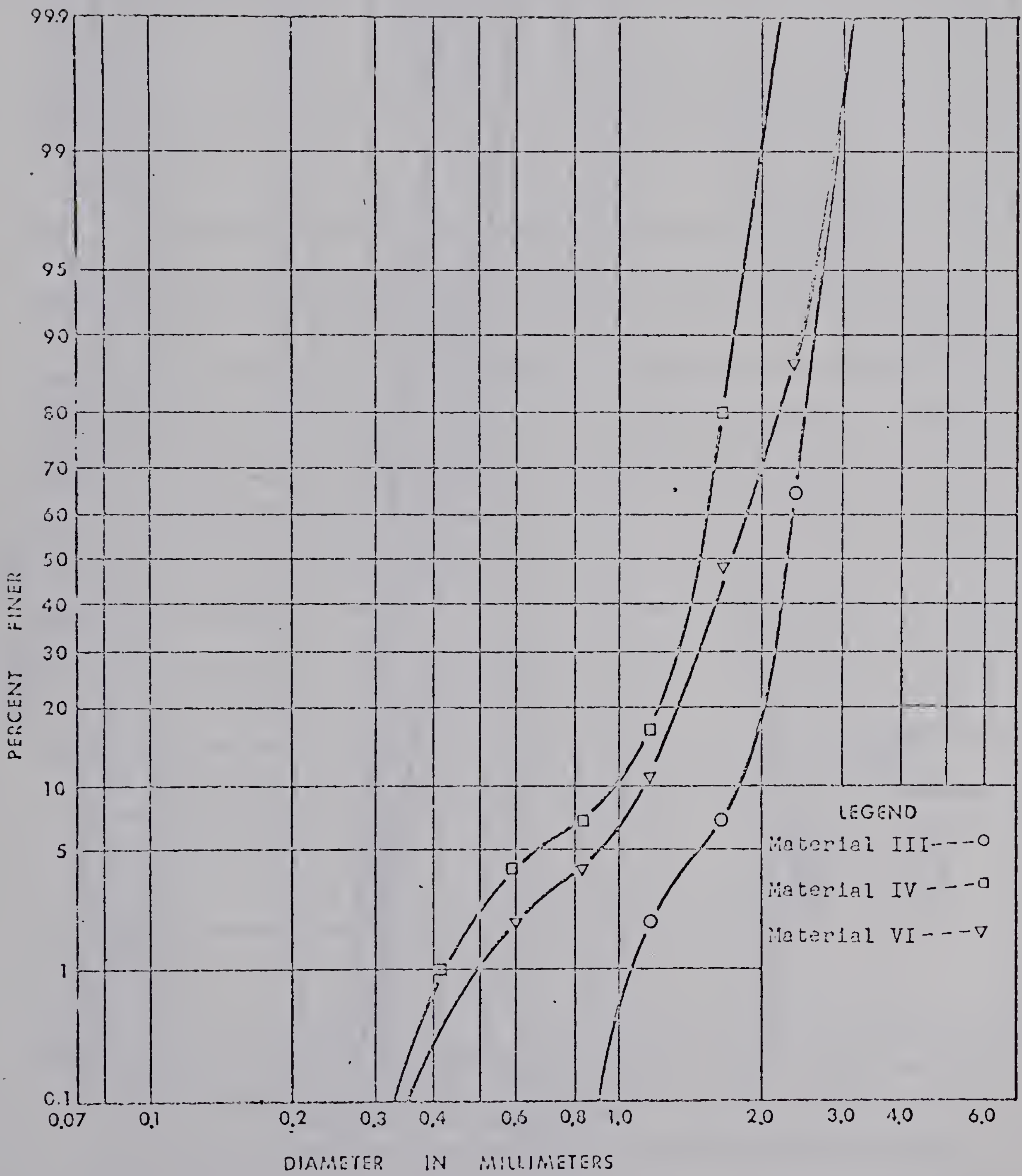



FIGURE C-13 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED IN T.Y. LIU EXPERIMENTS

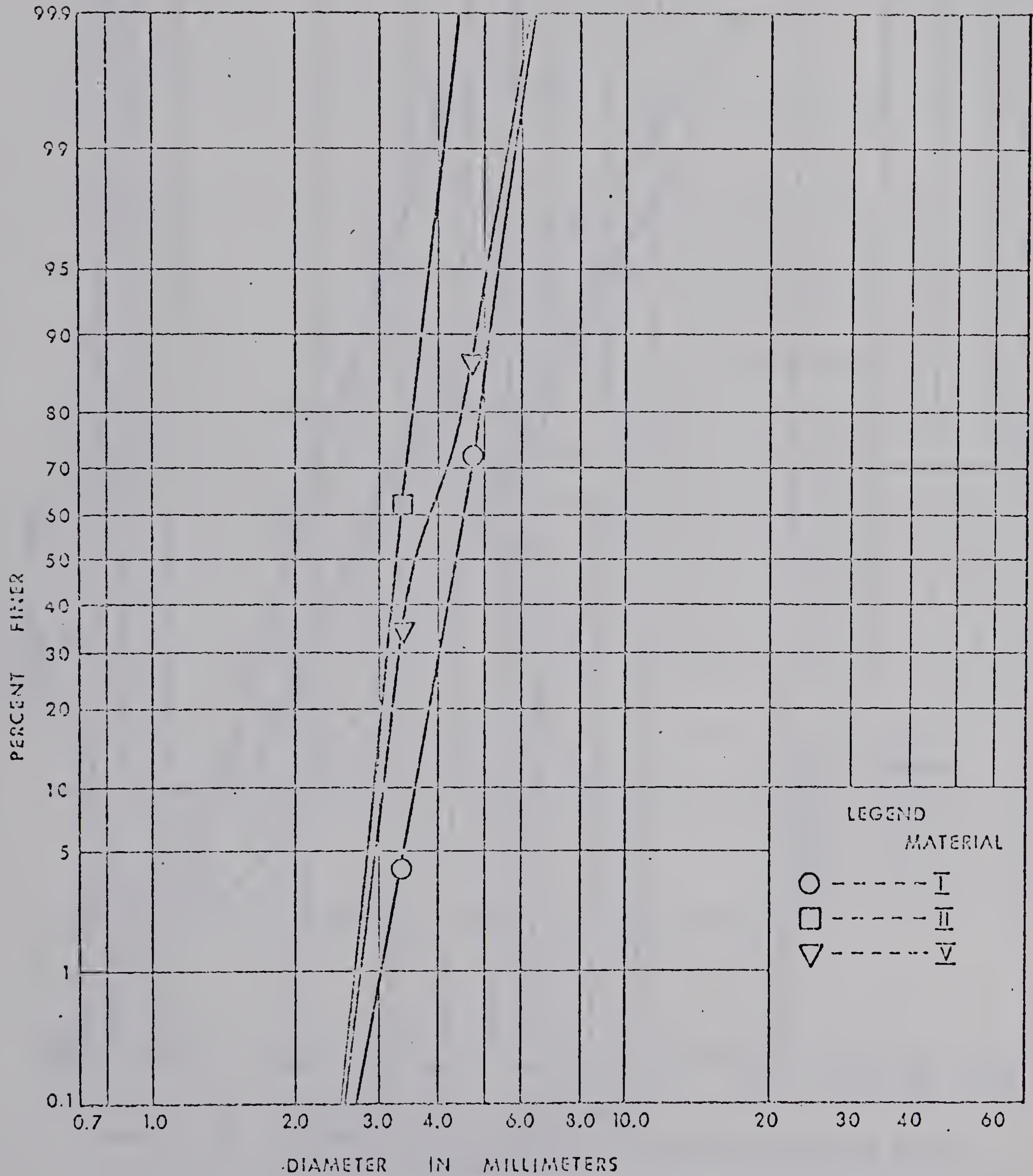



FIGURE C-14 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED IN T.Y. LIU EXPERIMENTS

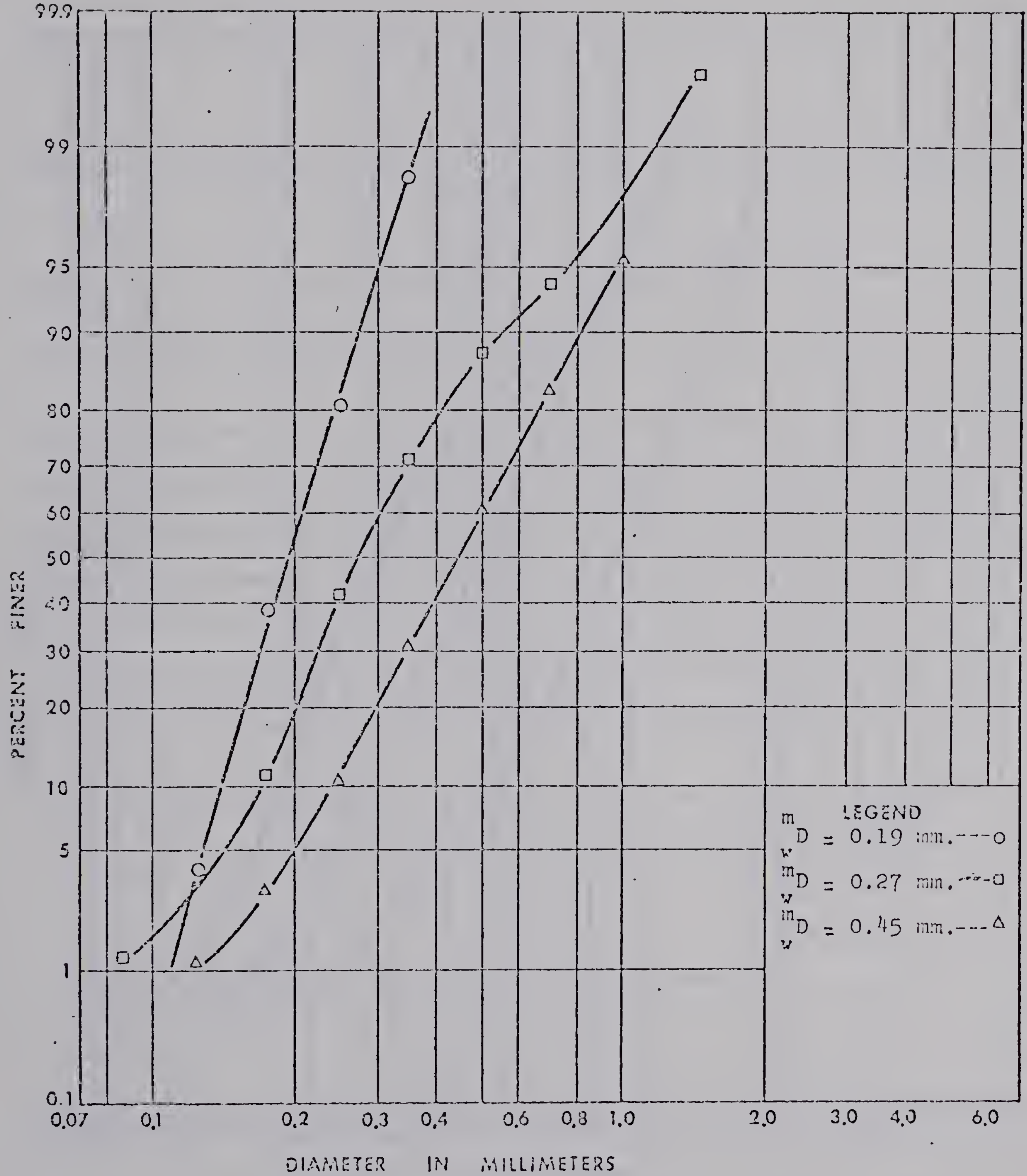



FIGURE C-15 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED IN C.S.U. EXPERIMENTS

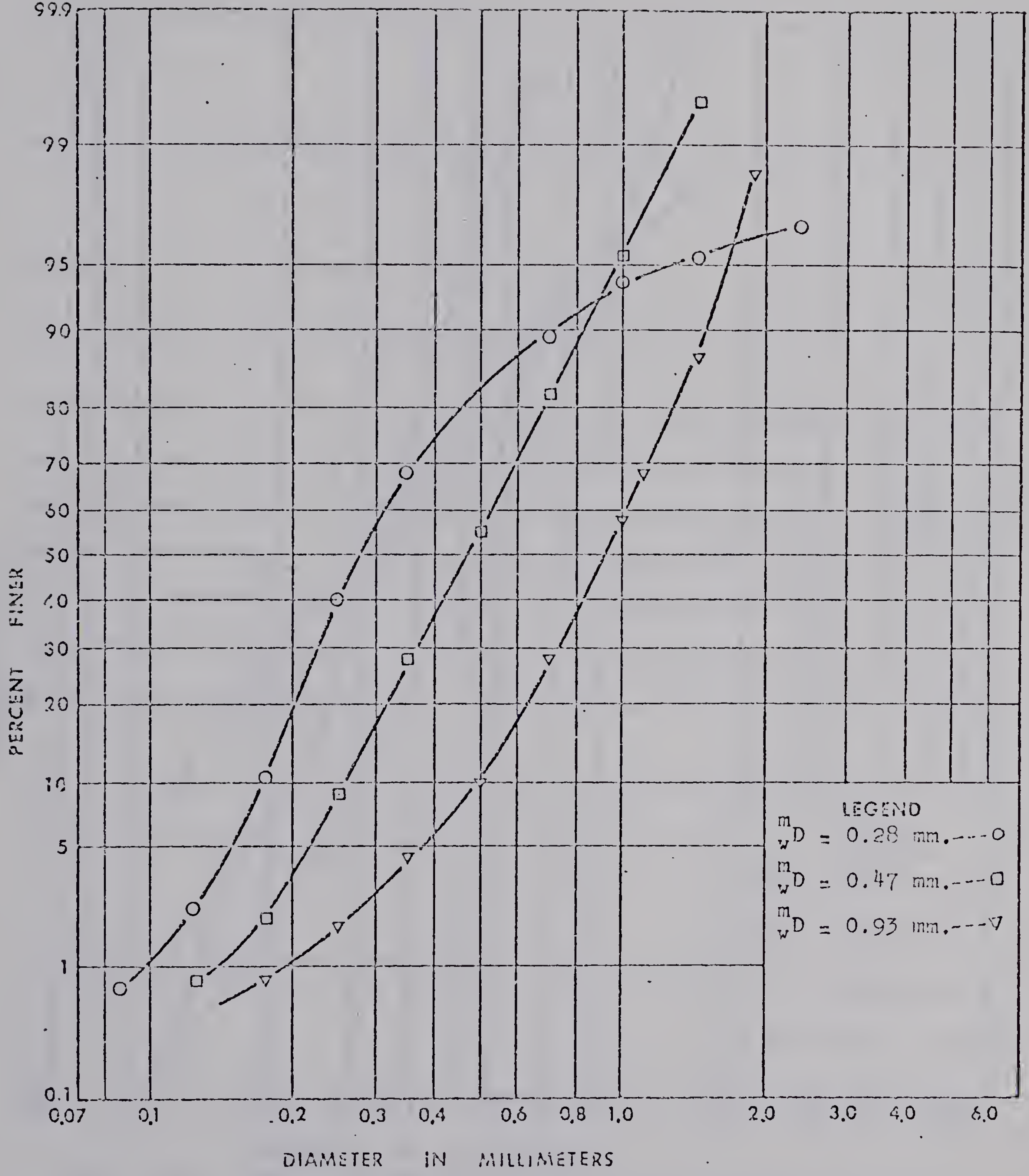



FIGURE C-16. GRAIN SIZE DISTRIBUTION CURVES FOR MATERIALS USED IN C.S.U. EXPERIMENTS

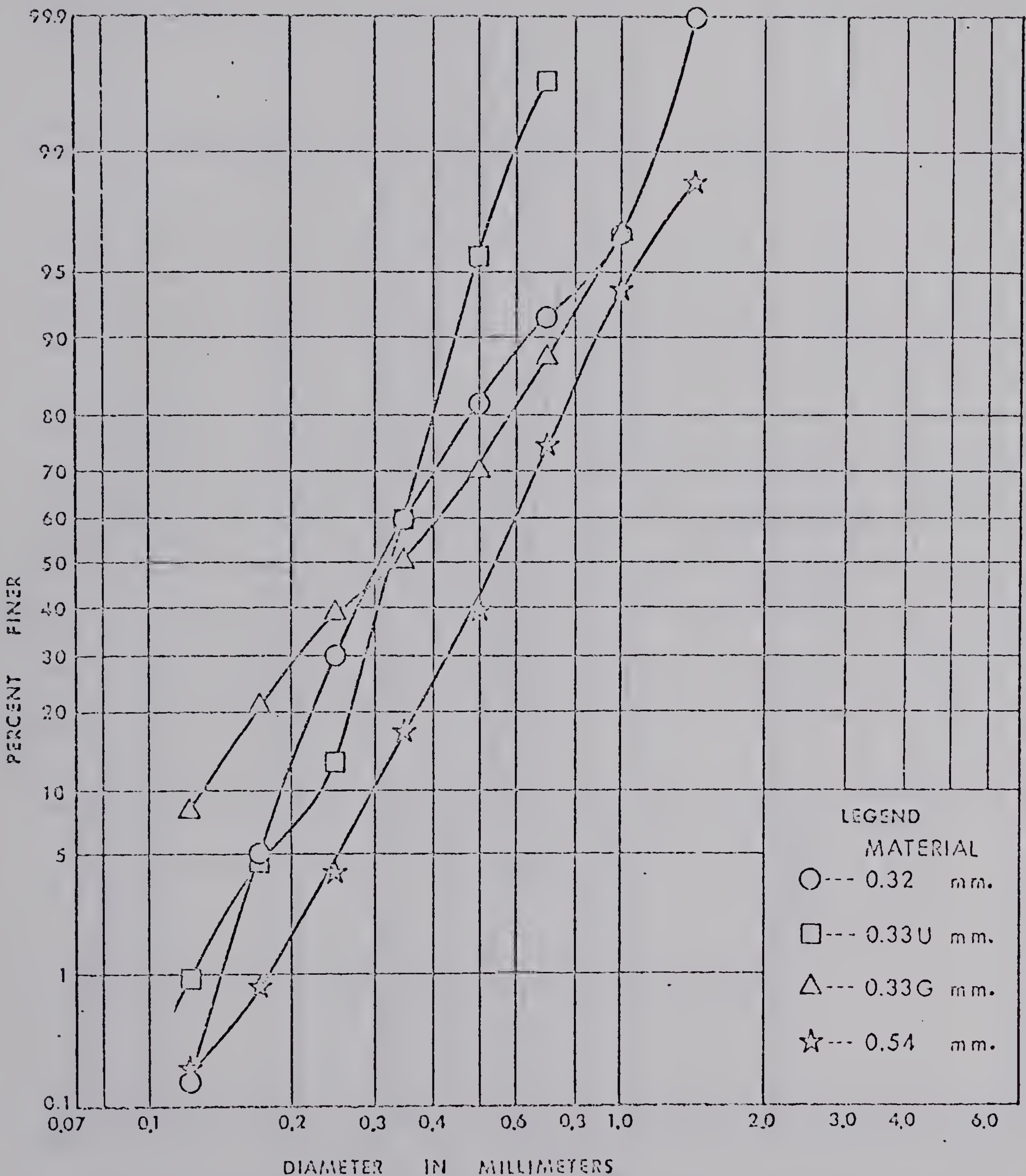



FIGURE C-17 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED IN C.S.U. EXPERIMENTS

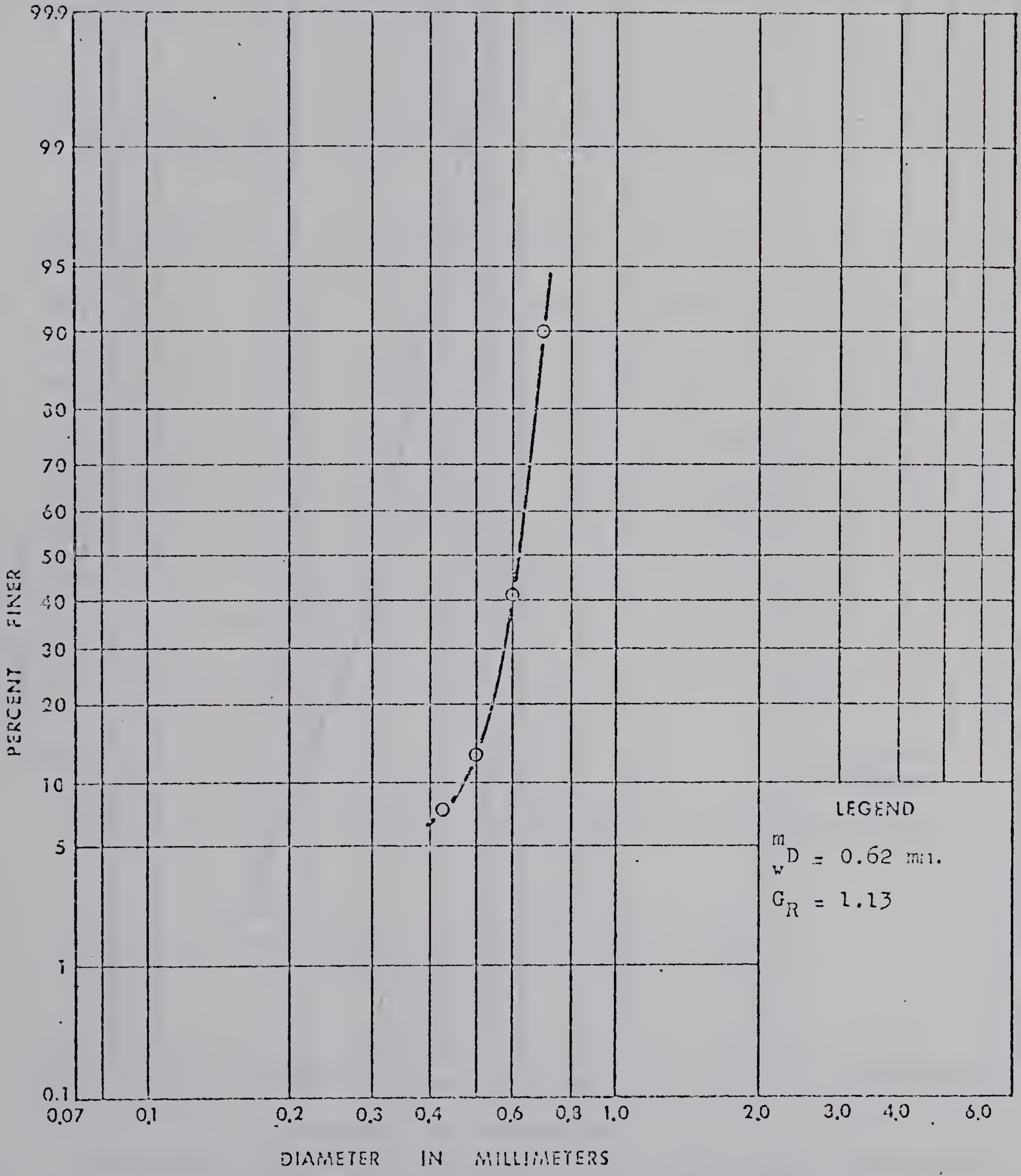



FIGURE C-18 - GRAIN SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY B. SINGH

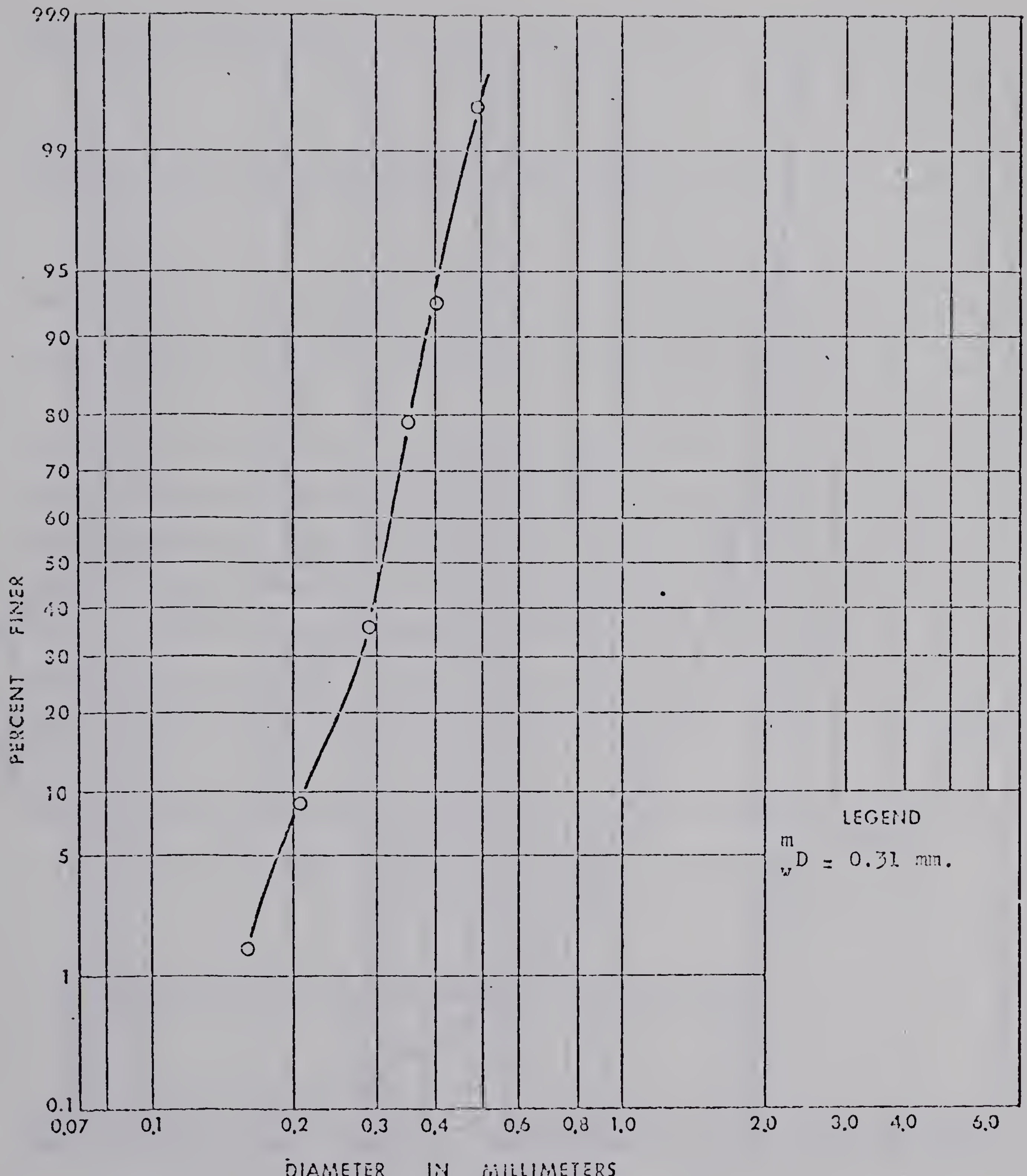



FIGURE C-19 - GRAIN SIZE DISTRIBUTION CURVE FOR MATERIALS USED IN WEST BENGAL RIVER RESEARCH INSTITUTE EXPERIMENTS

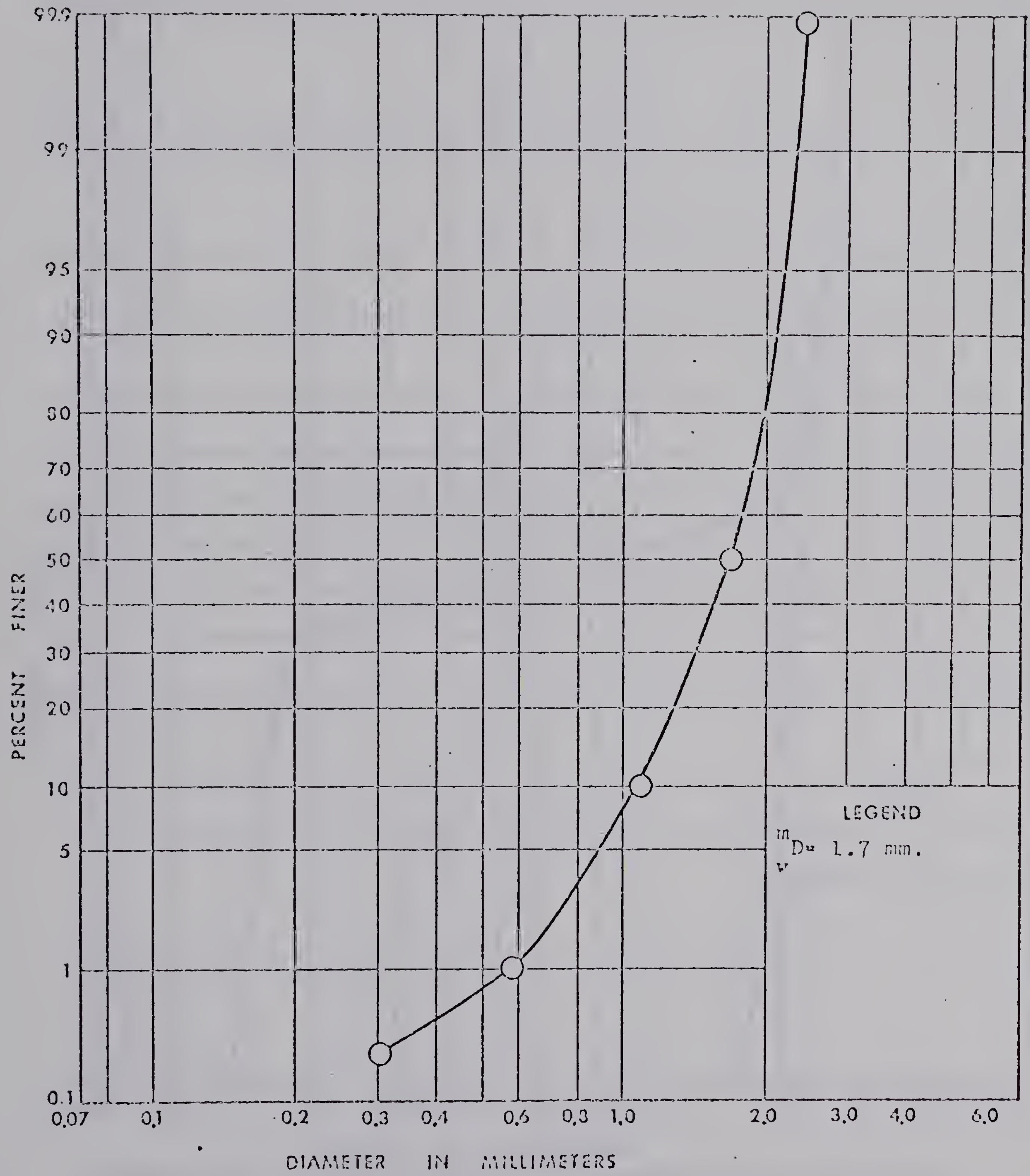



FIGURE C-20 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIAL USED BY BHATTACHRYA

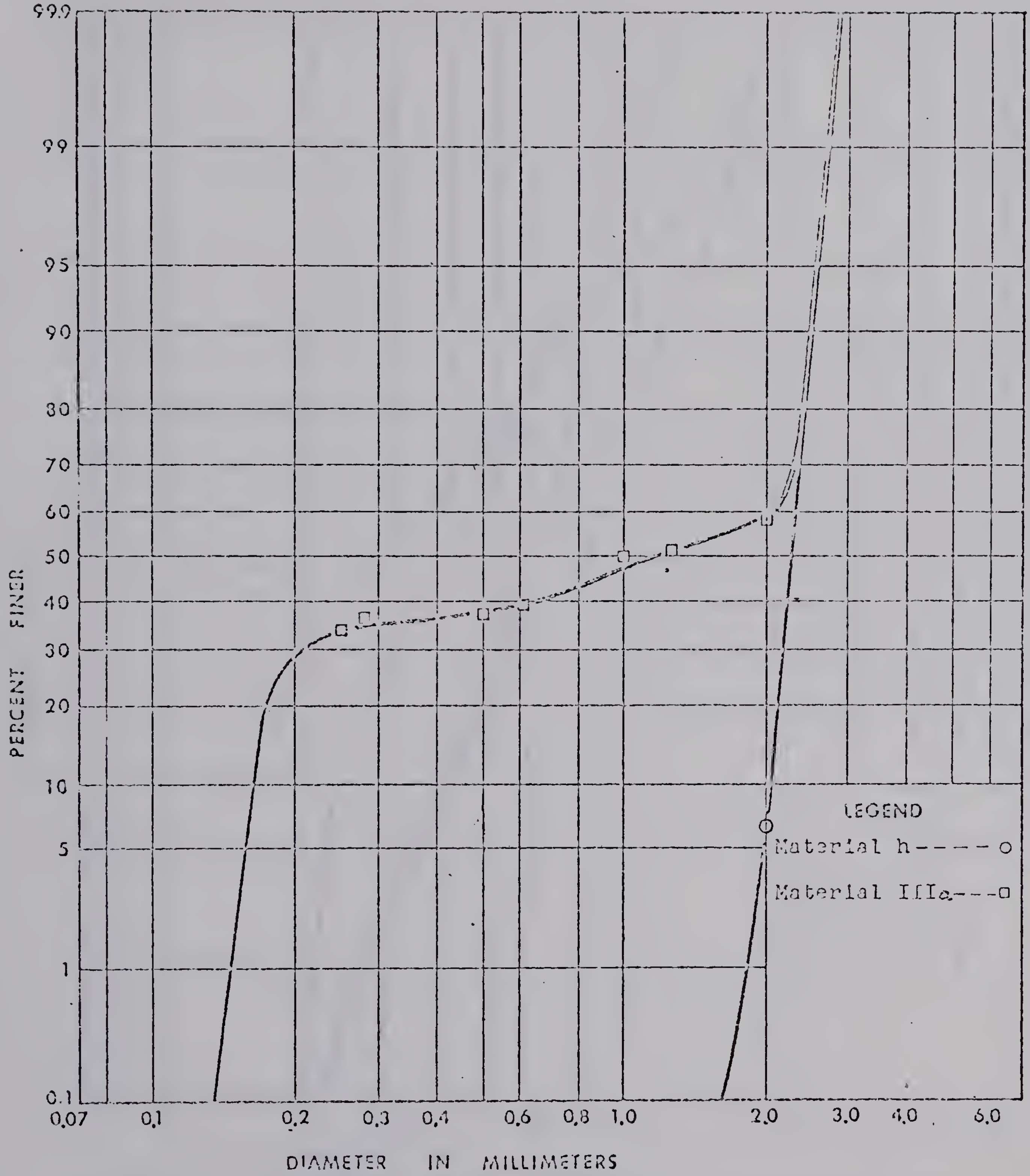



FIGURE C-21 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED BY H. J. CASEY

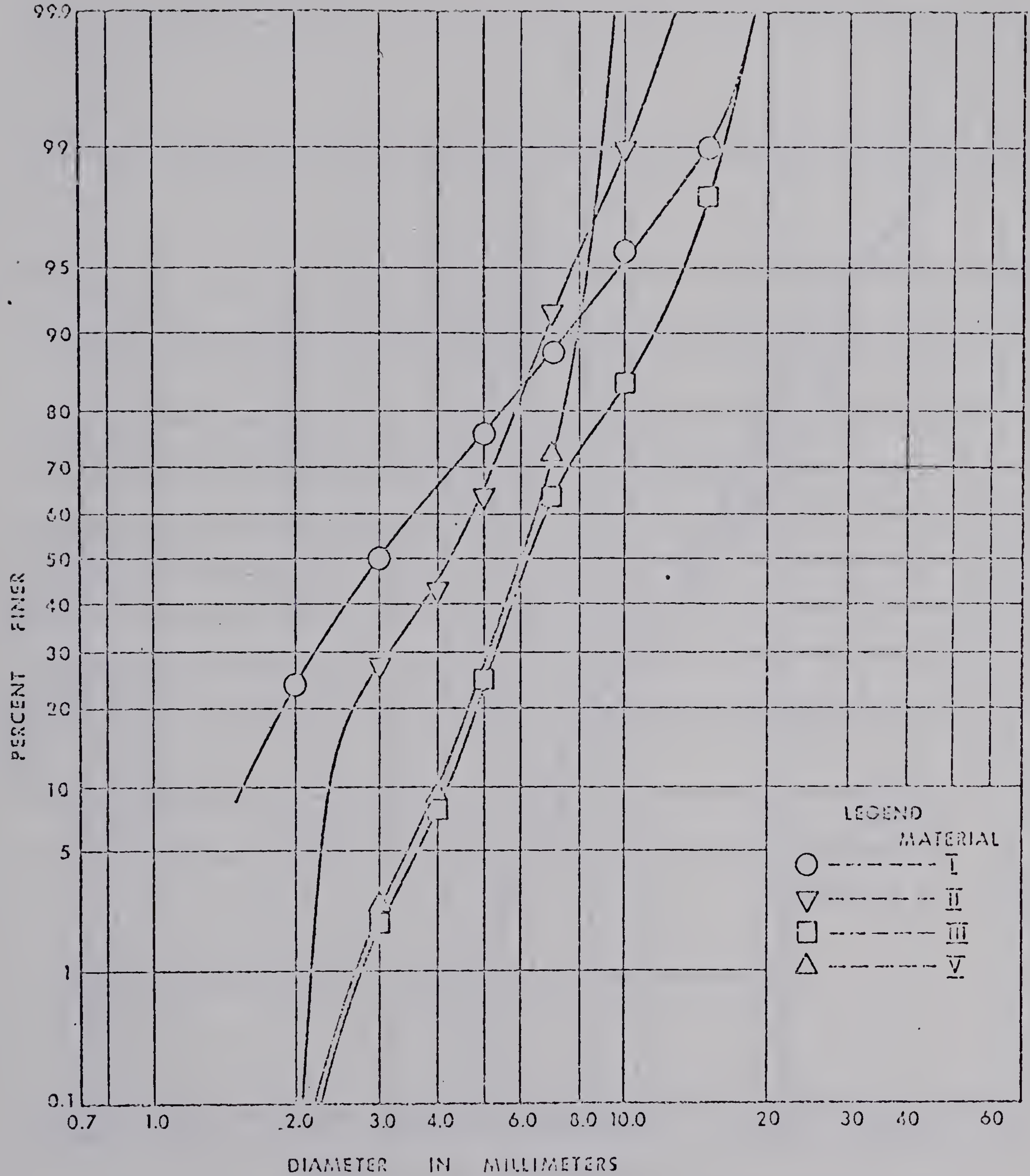



FIGURE C-22 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED BY HO PANG, YUNG

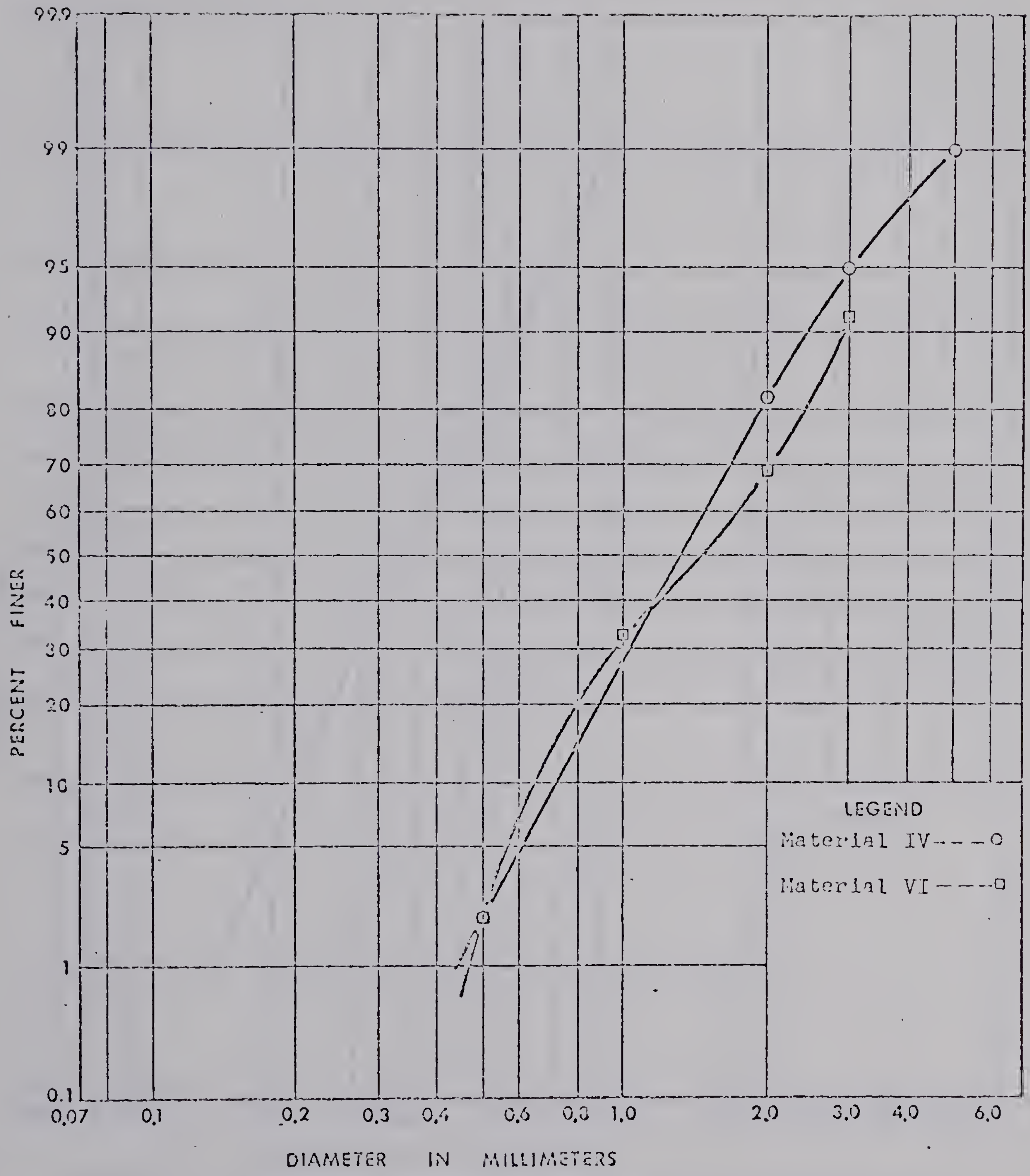



FIGURE C-23 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED BY HO PANG, YUNG

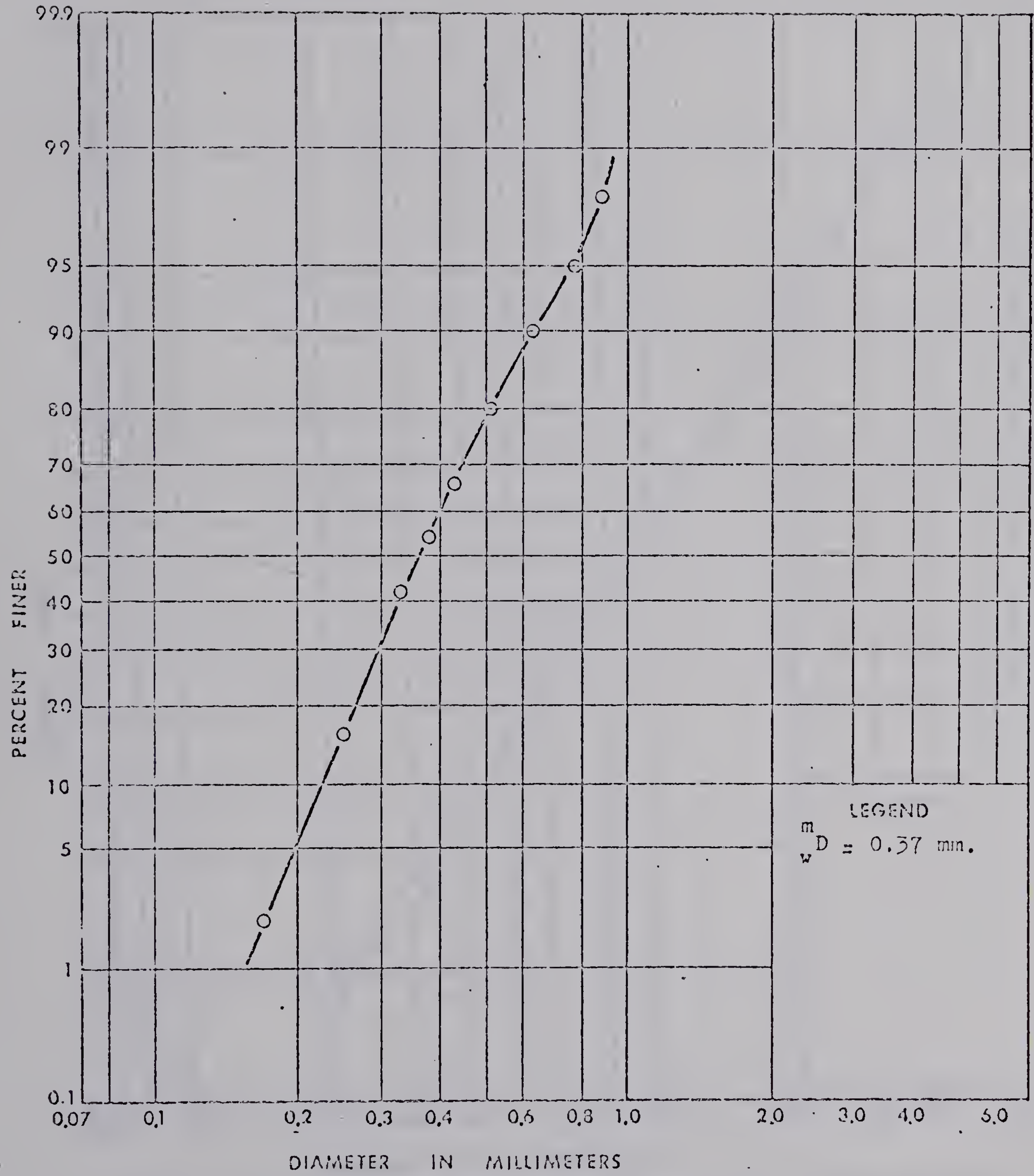



FIGURE C-24 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY M. P. O'BRIEN

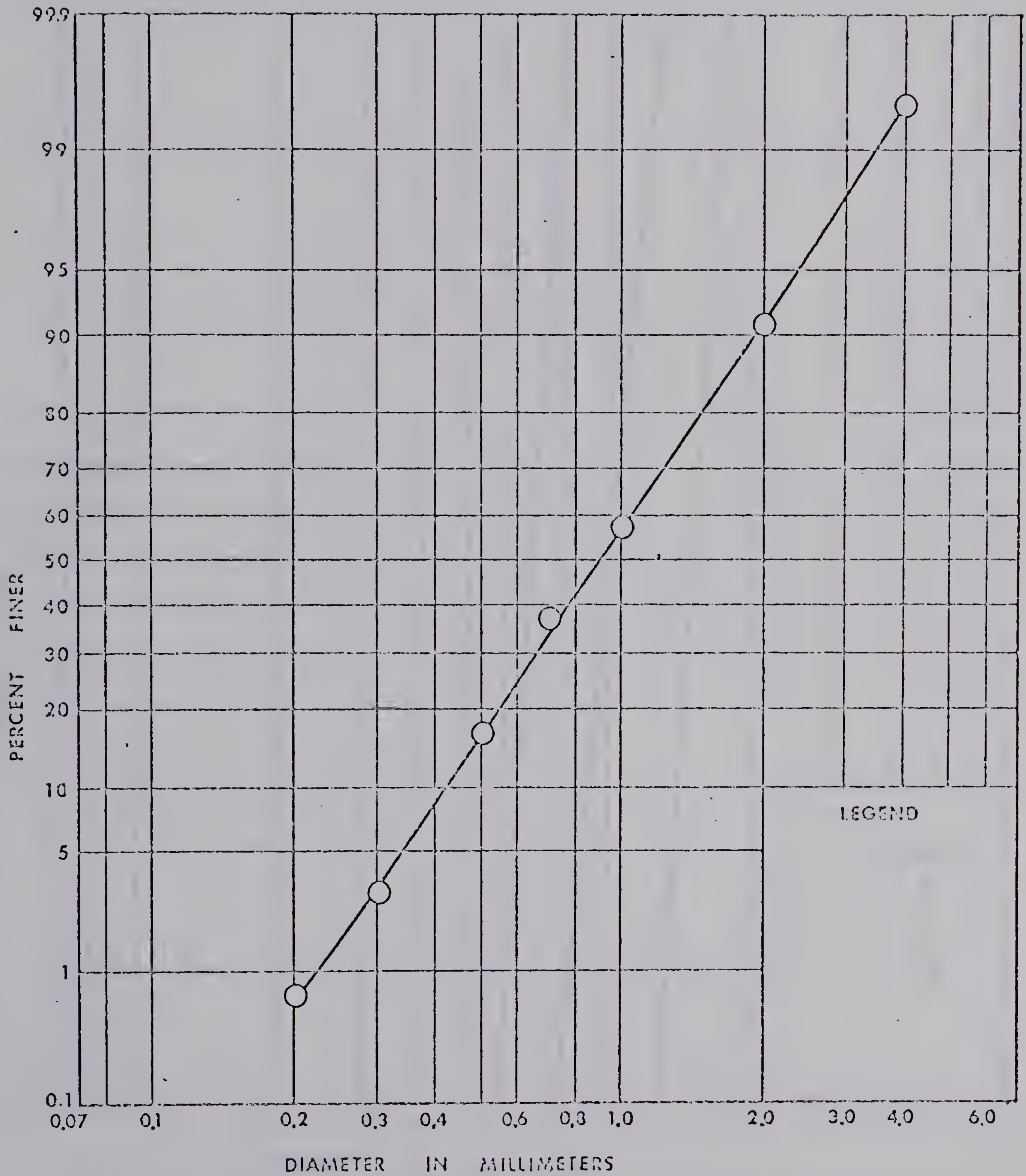



FIGURE C-25 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY H. A. EINSTEIN

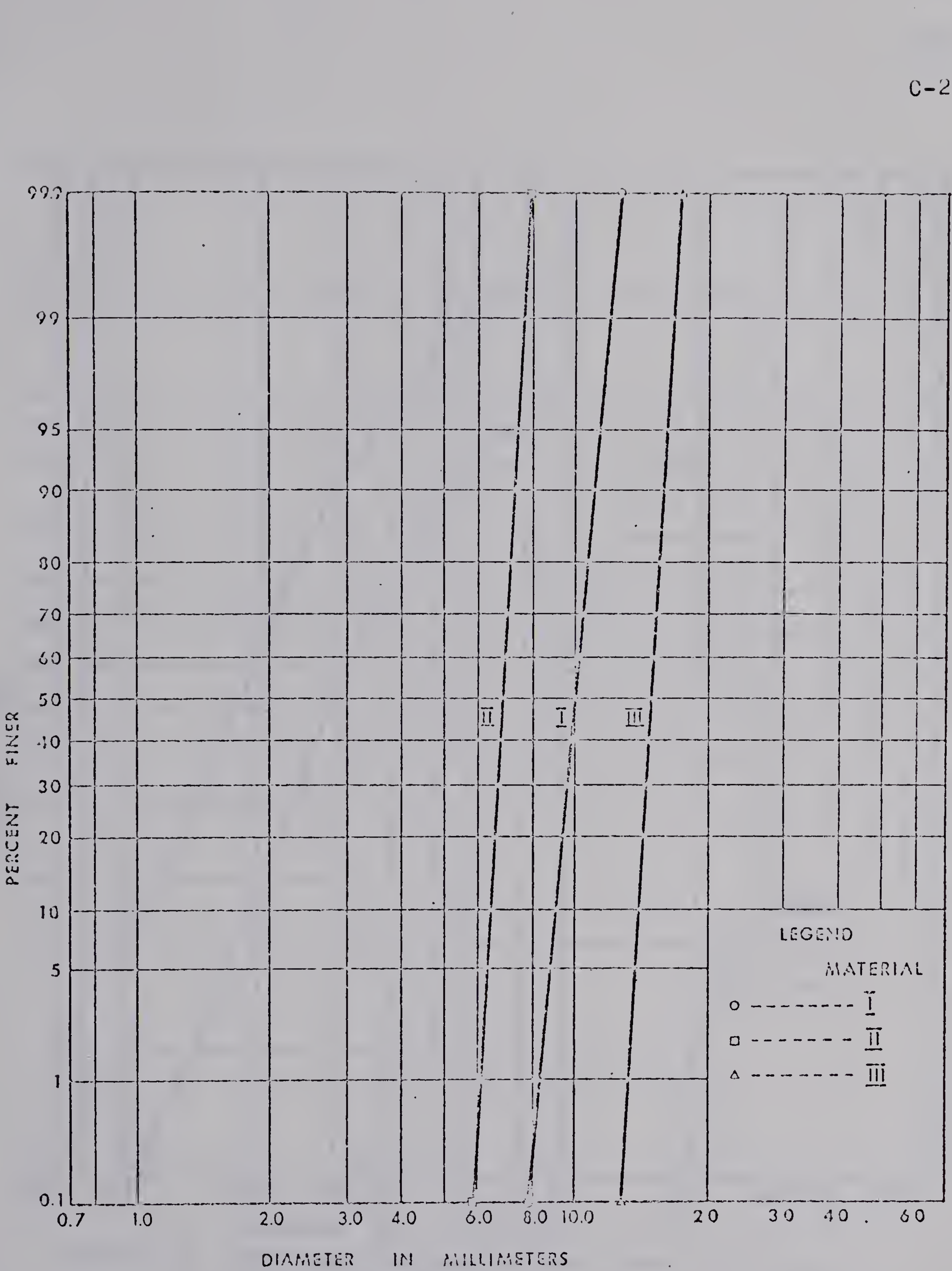



FIGURE C-26 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED BY BOGARDI & YEN

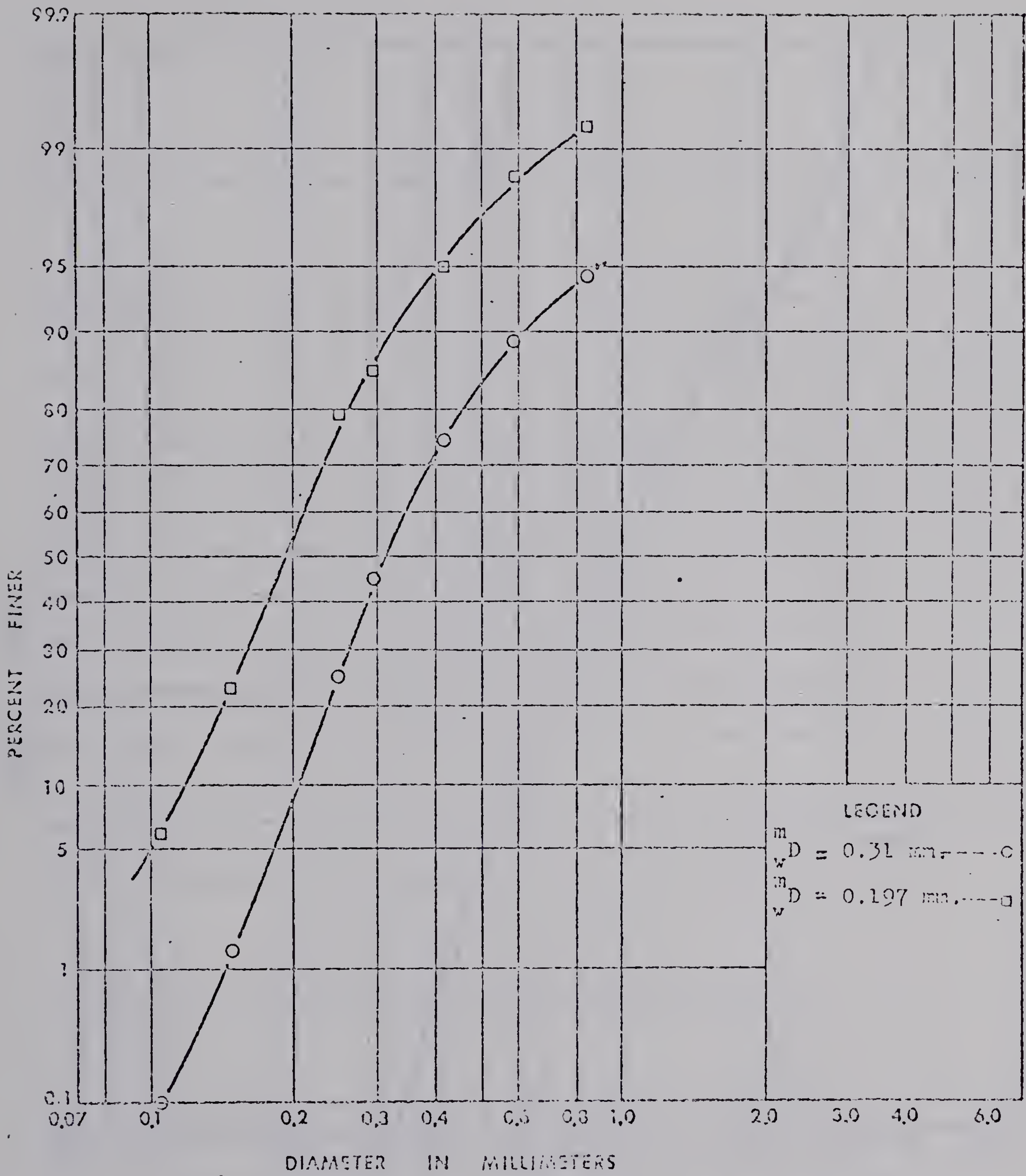



FIGURE C-27 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED IN U.B.C. EXPERIMENTS

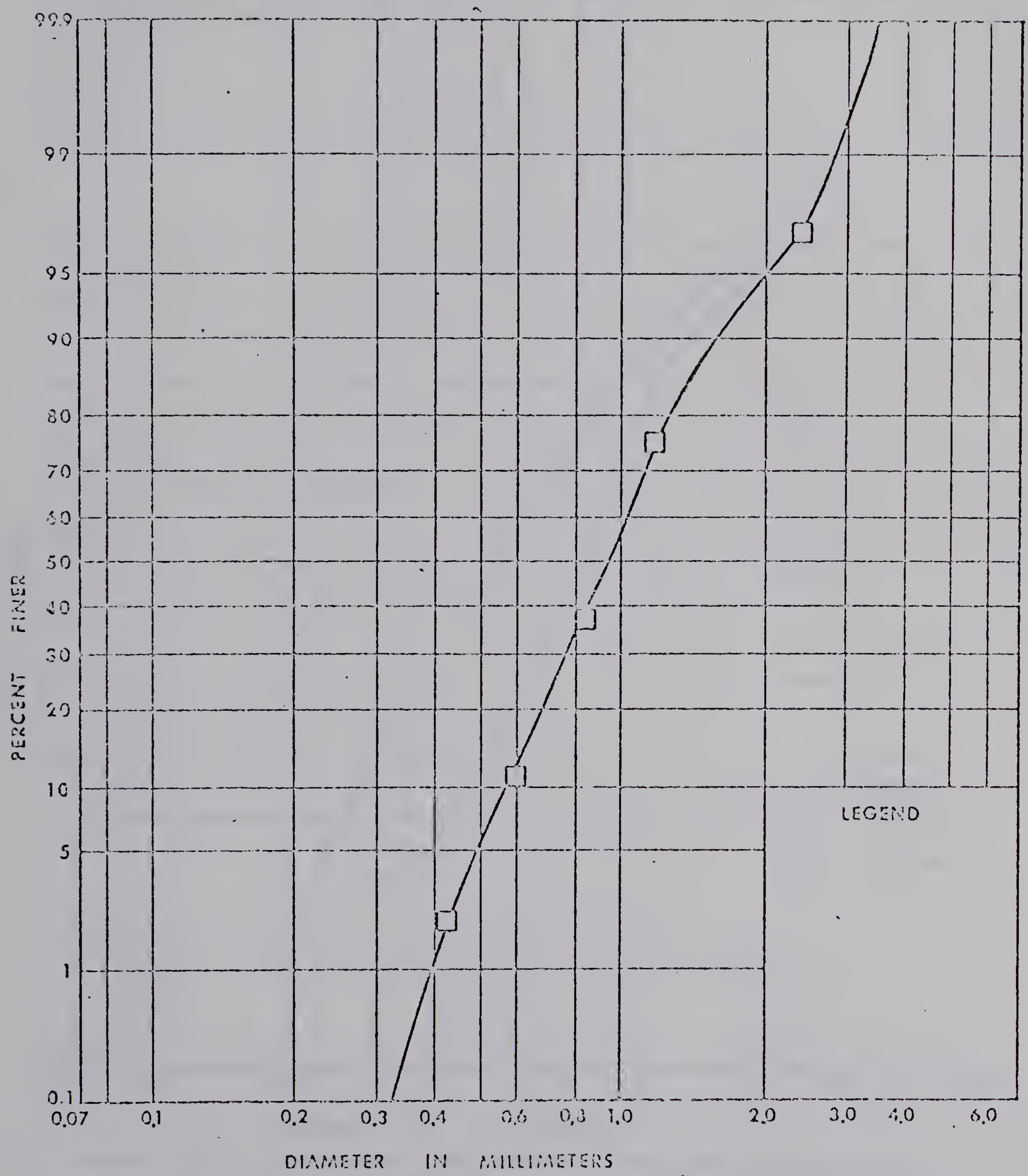



FIGURE C-28 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY MacDOUGALL

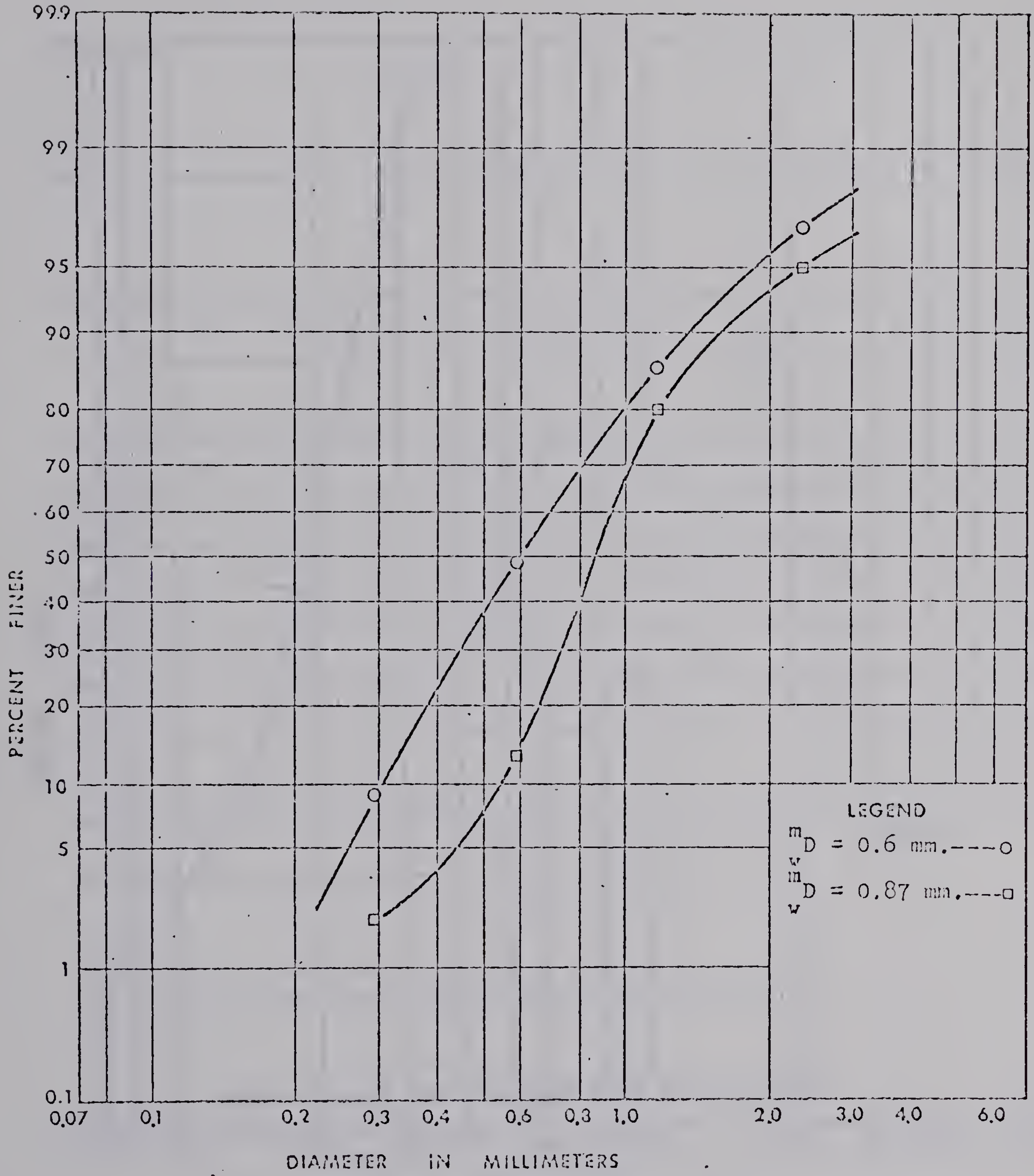



FIGURE C-29 - GRAIN-SIZE DISTRIBUTION CURVES FOR MATERIALS USED BY A. L. JORISSEN

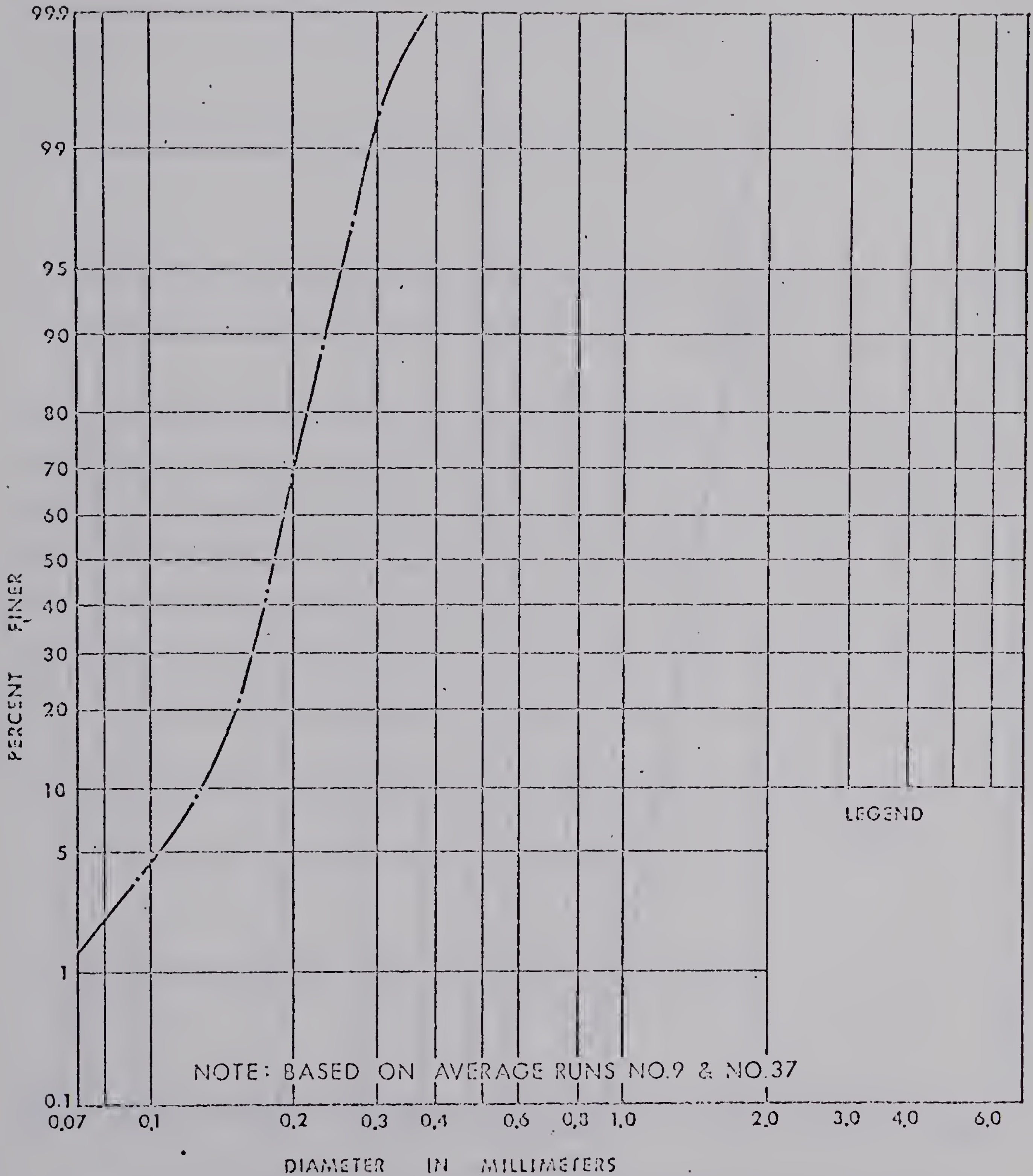



FIGURE C-30 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY BARTON & LIN

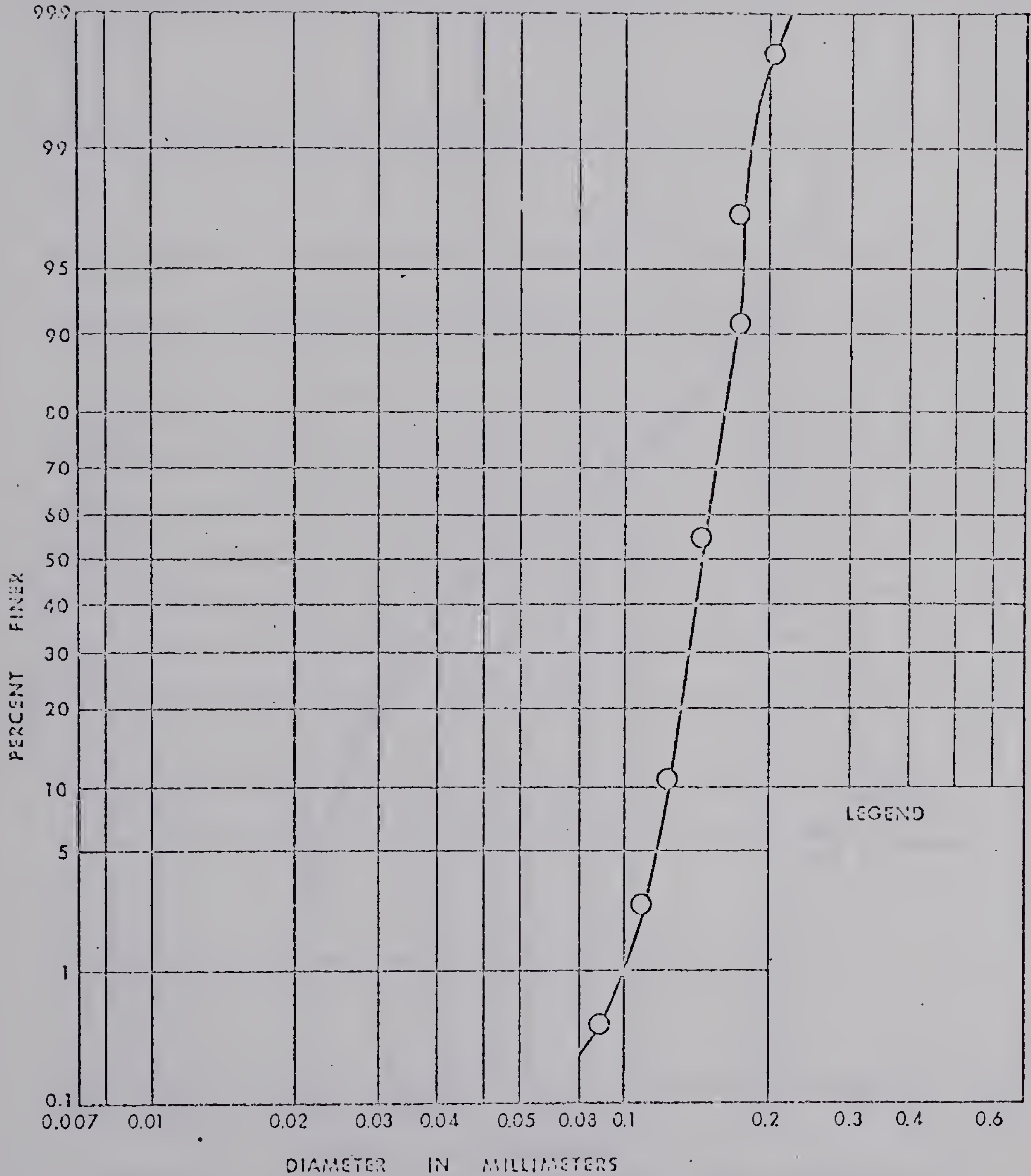



FIGURE C-31 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY VANONI & BROOK

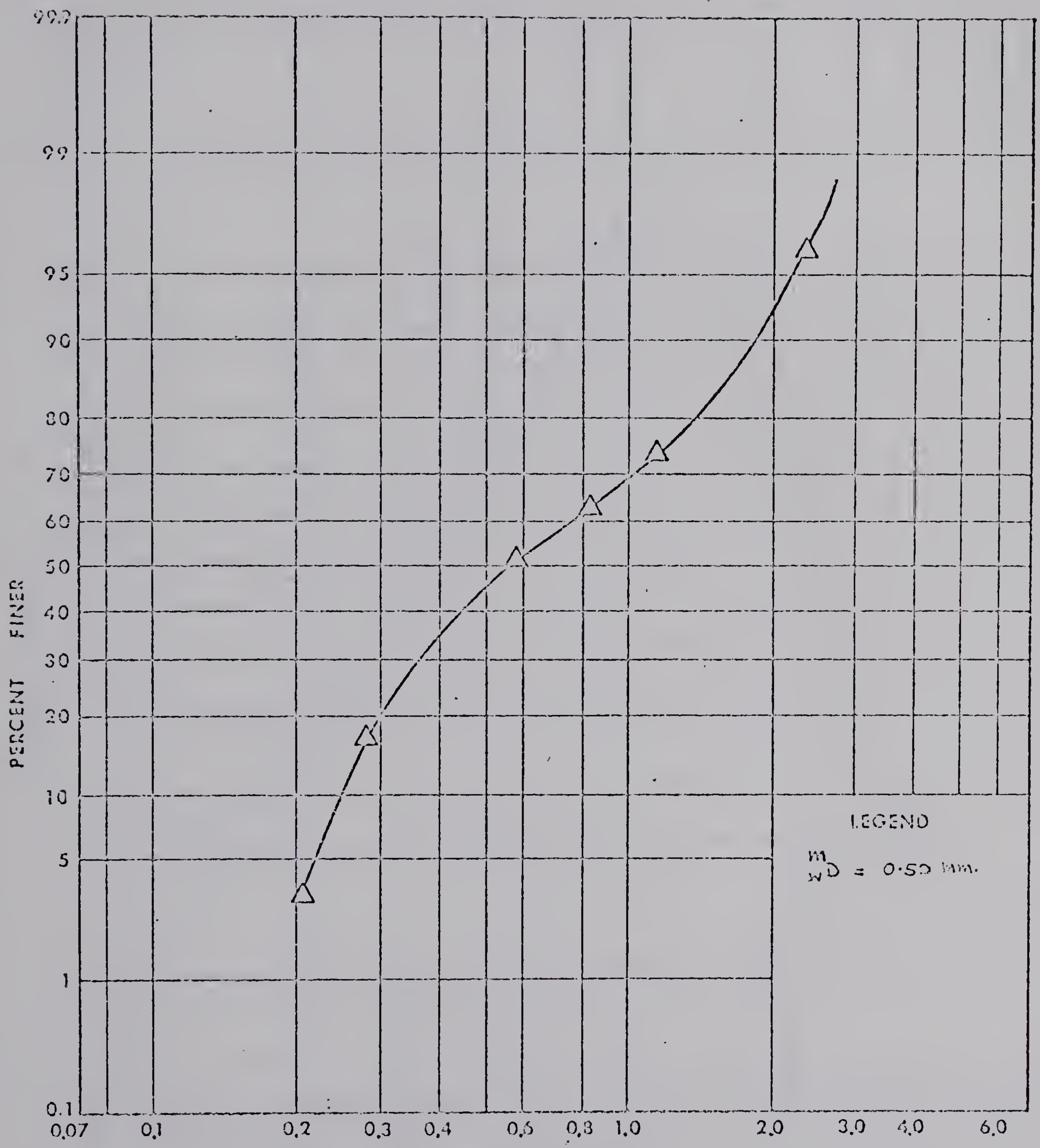



FIGURE C-32 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY S. D. CHYN

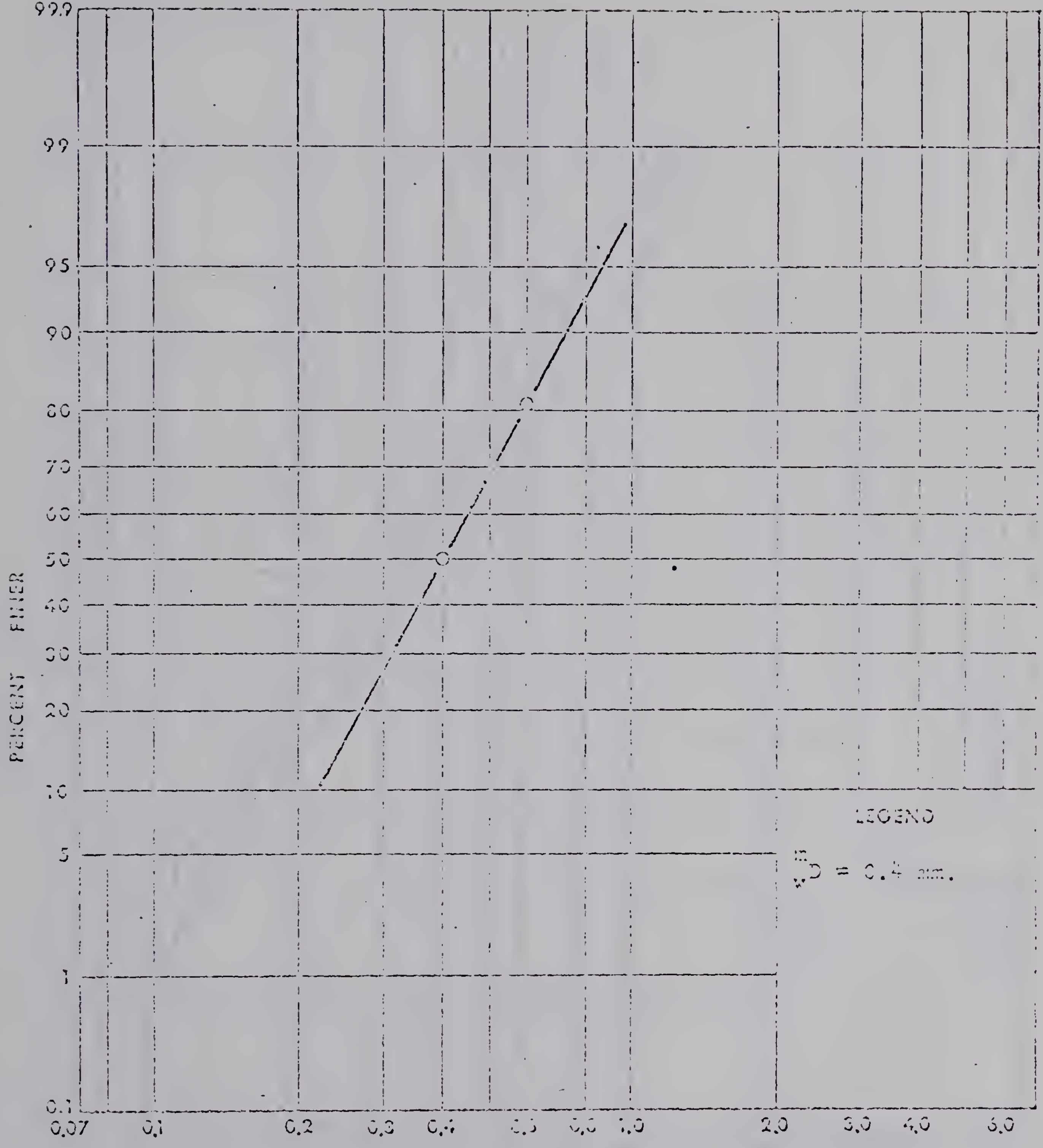



FIGURE C-33 - GRAIN-SIZE DISTRIBUTION CURVE FOR MATERIALS USED BY STEIN

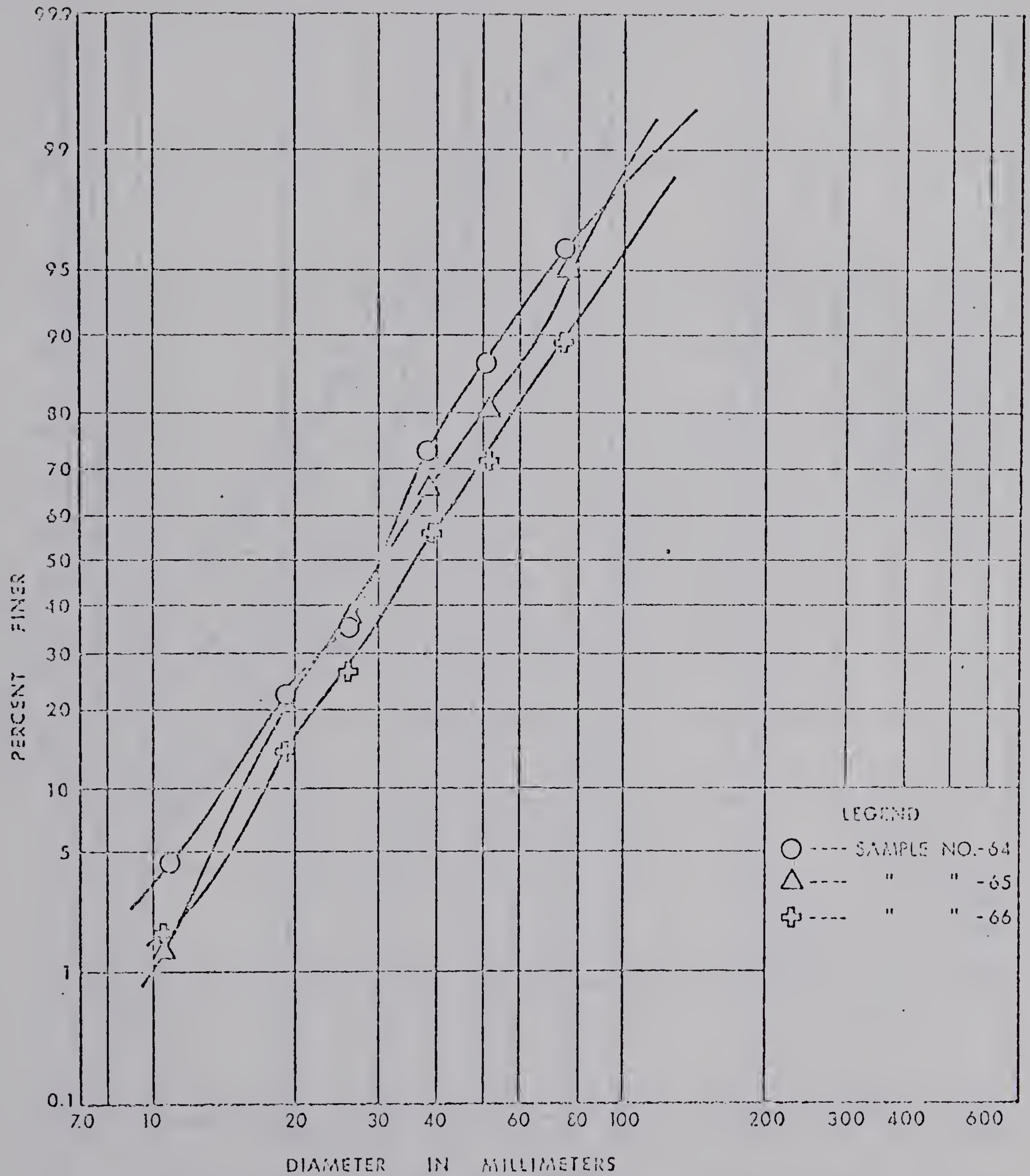



FIGURE C-34 - GRAIN-SIZE DISTRIBUTION CURVES FOR THE ELBOW RIVER BED-MATERIALS

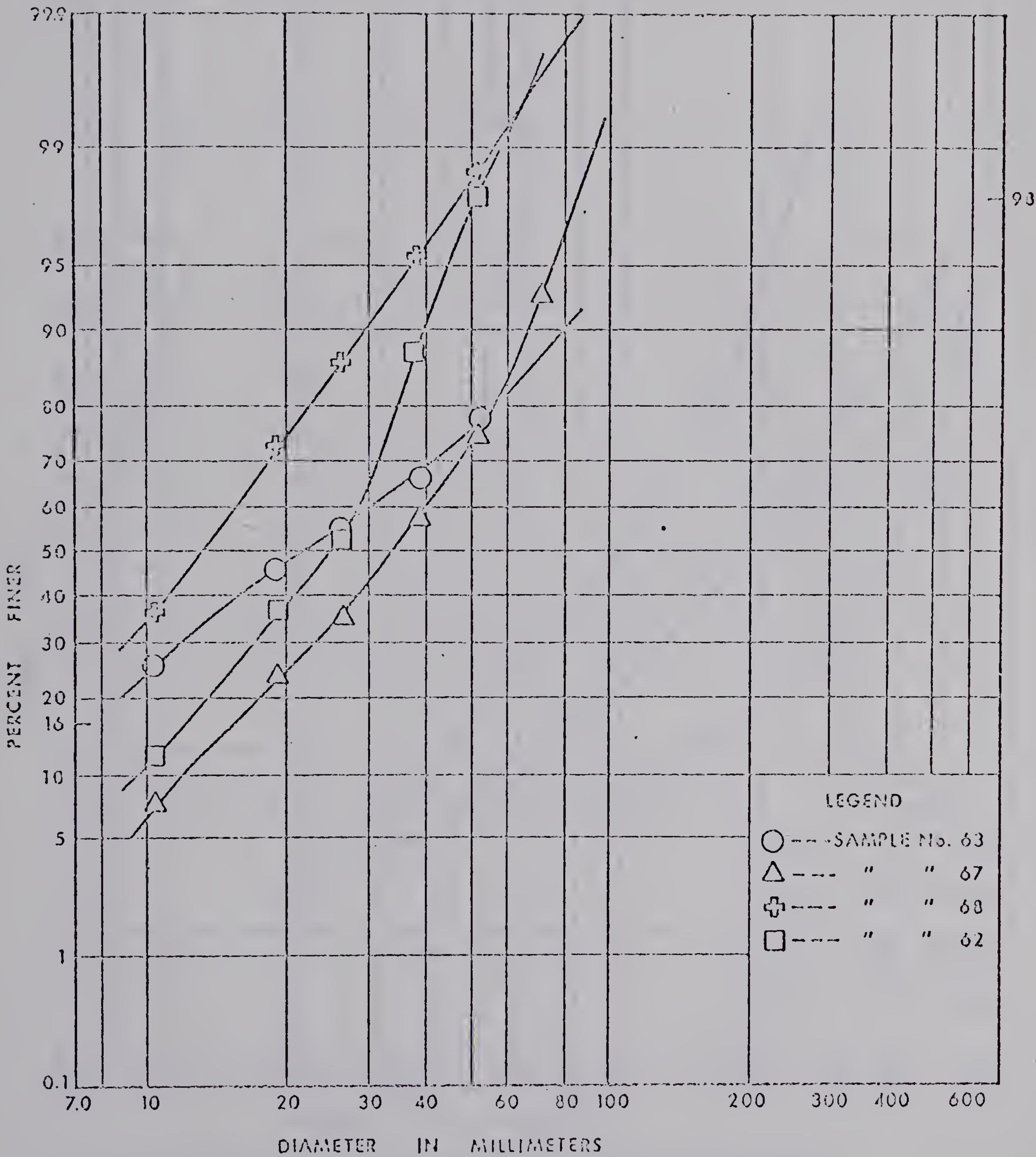



FIGURE C-35 - GRAIN-SIZE DISTRIBUTION CURVES FOR THE ELBOW RIVER BED-MATERIALS

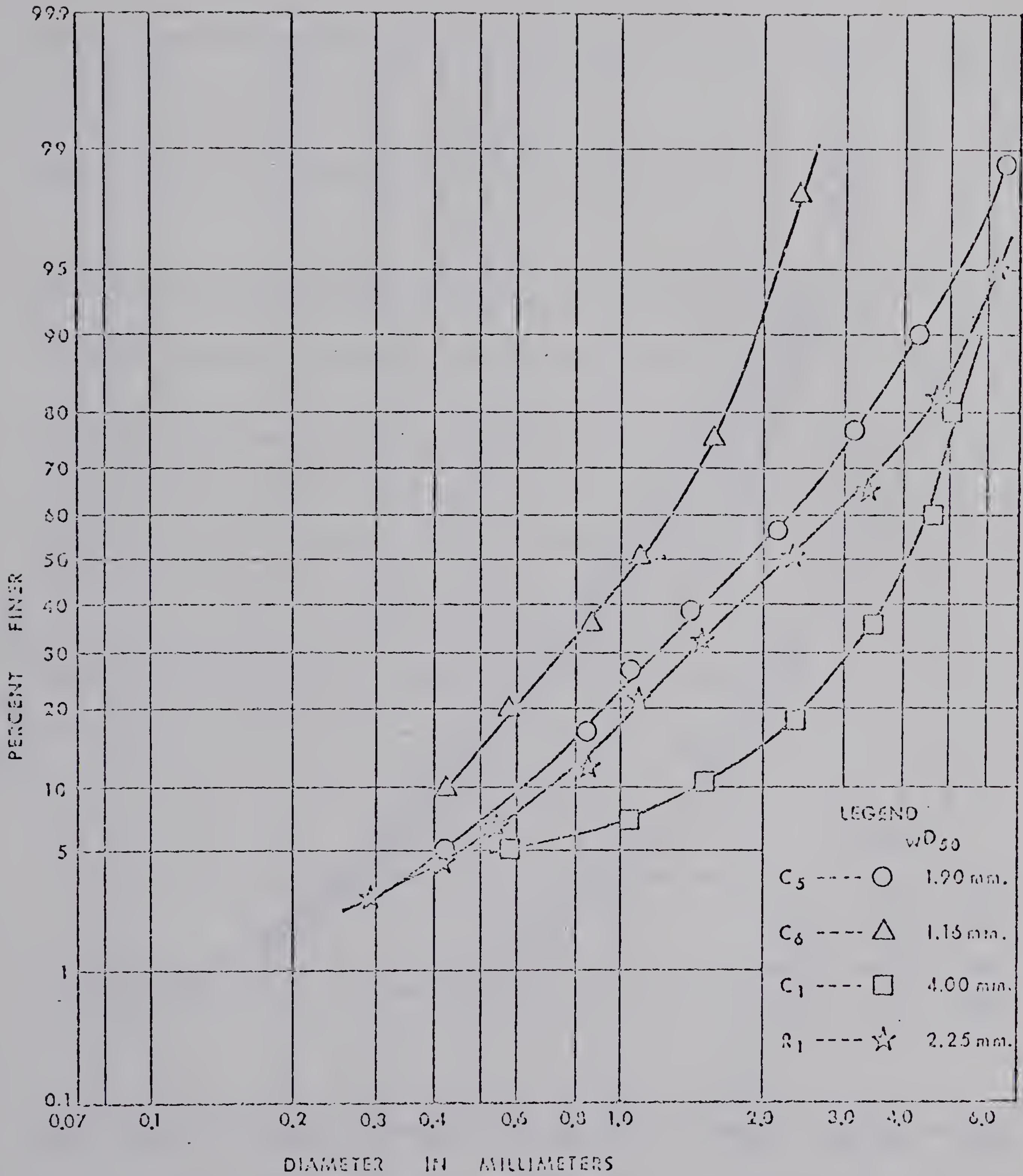



FIGURE C-36 - GRAIN SIZE DISTRIBUTION CURVES FOR LIGHT WEIGHT MATERIALS USED IN U.S.W.E.S. EXPERIMENTS

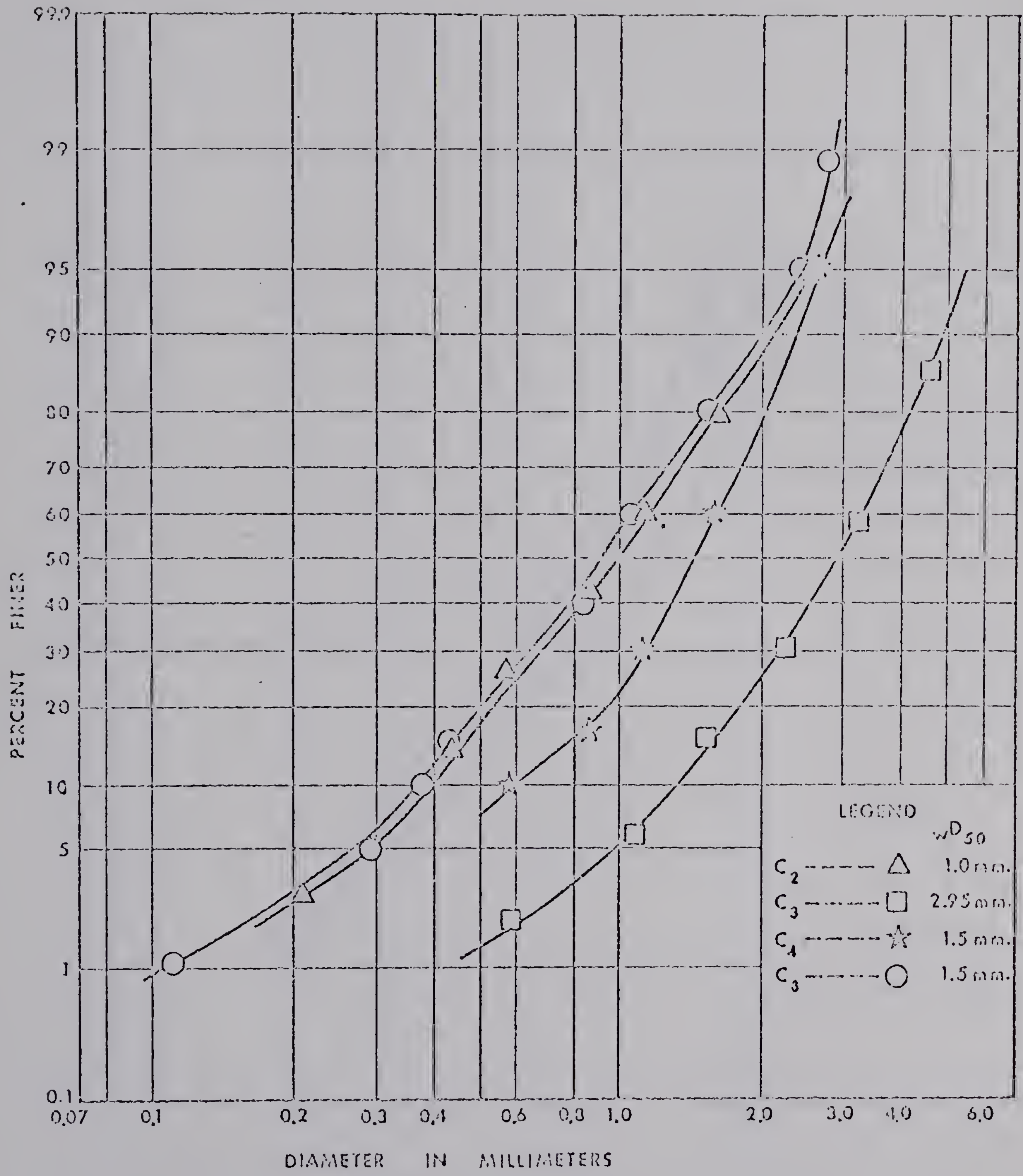



FIGURE C-37 - GRAIN SIZE DISTRIBUTION CURVES FOR LIGHT WEIGHT MATERIALS USED IN U.S.W.E.S. EXPERIMENTS

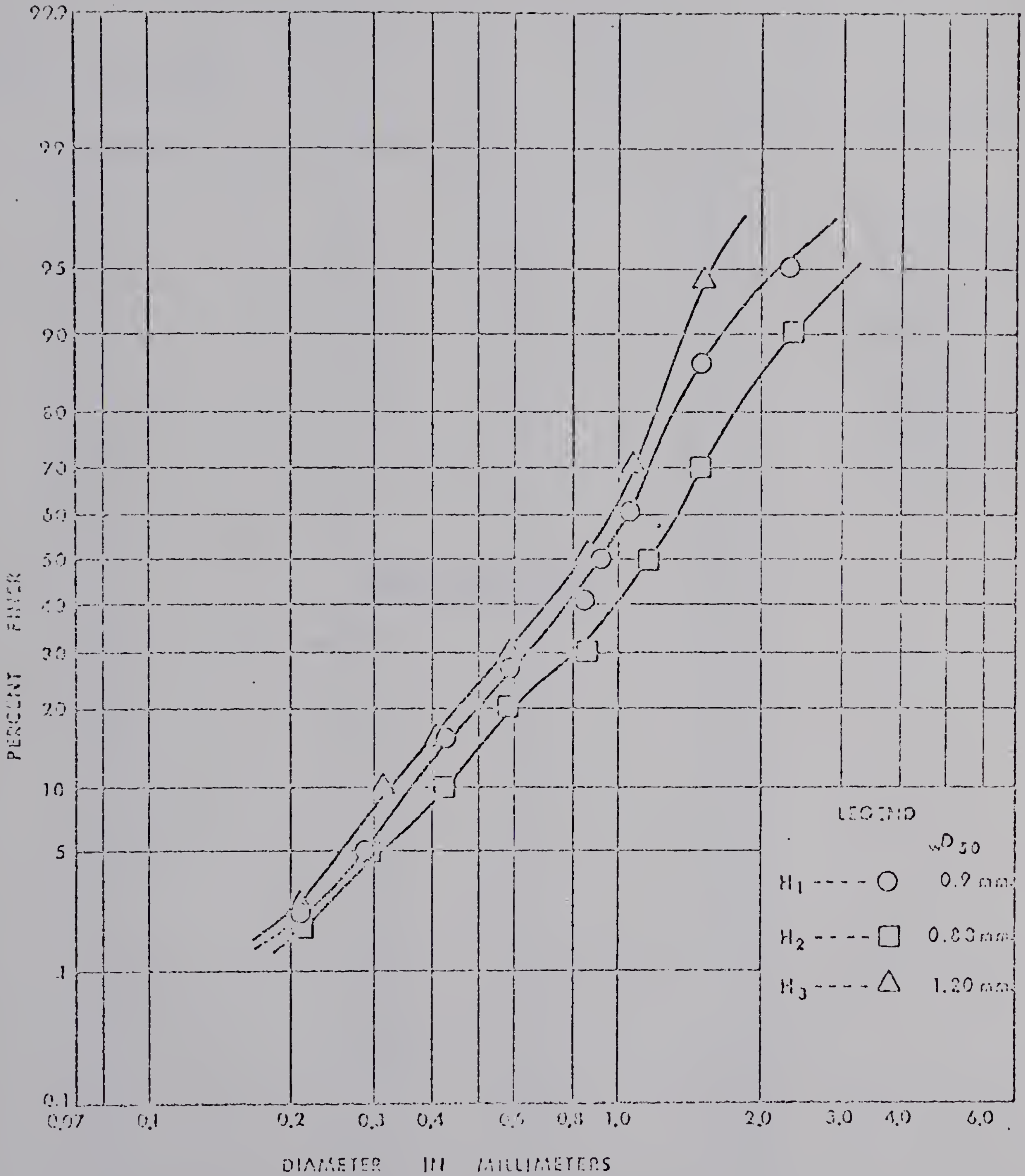



FIGURE C-38 - GRAIN SIZE DISTRIBUTION CURVES FOR LIGHT WEIGHT MATERIALS USED IN U.S.W.E.S. EXPERIMENTS

APPENDIX "D"

TABLE D-1

THE ELBOW RIVER DATA (REF. 35)

| OBSERVED | | | | |
|---|---|---|---|---|
| Unit discharge cfs/ft. | C P.P.H.T. | d ft. | Mean Velocity V ft./sec. | Remarks |
| 8.7 | 0.0 | 1.9 | 4.59 | |
| 13.9 | 8.5 | 2.2 | 6.34 | Average ${}_{w}^{m}D$ was |
| 25.3 | 0.0 | 3.2 | 7.90 | taken to be 0.1 f |
| 25.3 | 0.17 | 3.2 | 7.9 | for all calcula- |
| 25.3 | 0.53 | 3.2 | 7.9 | tions. |
| 30.3 | 0.14 | 3.9 | 7.77 | Specific gravity |
| 30.3 | 0.34 | 3.9 | 7.77 | 2.65. Overall |
| 30.3 | 0.02 | 3.9 | 7.77 | slope of the |
| 38.8 | 0.0 | 5.6 | 6.94 | reach was re- |
| 13.0 | 0.0 | 2.2 | 5.90 | ported to be |
| 13.1 | 0.0 | 1.8 | 7.28 | $7.45 \times 10^{-3}$ |
| 12.2 | 0.0 | 2.0 | 6.12 | |
| 15.5 | 0.05 | 2.3 | 6.73 | |
| 18.8 | 0.01 | 2.5 | 7.54 | |
| 17.5 | 0.0 | 2.5 | 7.01 | |
| 25.3 | 0.0 | 3.8 | 6.65 | |
| 30.5 | 0.0 | 5.1 | 5.96 | |
| 13.5 | 0.0 | 2.2 | 6.12 | |
| 13.5 | 0.07 | 2.2 | 6.12 | |
| 13.5 | 0.02 | 2.2 | 6.12 | |
| 13.5 | 0.0 | 2.2 | 6.12 | |
| 13.5 | 0.07 | 2.2 | 6.12 | |
| 13.5 | 0.05 | 2.2 | 6.12 | |
| 10 | 0.07 | 1.7 | 5.89 | |
| 10 | 0.19 | 1.7 | 5.89 | |
| 7.3 | 0.18 | 1.8 | 3.70 | |
| 13.1 | 0.1 | 1.8 | 7.28 | |
| 25.3 | 0.0 | 3.2 | 7.90 | |
| 15.5 | 0.05 | 2.3 | 6.73 | |
| 15.5 | 1.95 | 2.3 | 6.73 | |
| 12.2 | 0 | 2.0 | 6.12 | |
| 13.1 | 0 | 18 | 7.28 | |
| 13.1 | 0.1 | 1.8 | 7.28 | |
| 10.5 | 0.3 | 1.8 | 5.85 | |
| 16.3 | 4.4 | 2.3 | 7.07 | |
| 17.5 | 0.15 | 2.6 | 6.74 | |
| 10.5 | 7.3 | 1.8 | 5.85 | |
| 8.65 | 0 | 1.5 | 5.76 | |
| 12.6 | 0.11 | 2.0 | 6.29 | |

TABLE D-1 (CONTINUED)

| OBSERVED | | | | |
|---|---|---|---|---|
| Unit discharge cfs/ft. | C P.P.H.T. | d ft. | Mean Velocity V ft./sec. | Remarks |
| 16.3 | 0.15 | 2.3 | 7.07 | |
| 10.0 | 0 | 1.7 | 5.89 | |
| 10 | 0 | 1.7 | 5.89 | |
| 8.64 | 5.6 | 1.5 | 5.76 | |
| 17.5 | 3.2 | 2.6 | 6.74 | |
| 24.6 | 0 | 3.5 | 7.62 | |
| 28.6 | 0 | 4.5 | 6.35 | |
| 12.6 | 2.4 | 2.6 | 6.29 | |
| 10.5 | 5.4 | 1.8 | 5.85 | |
| 10.0 | 0.09 | 1.7 | 5.89 | |
| 8.64 | 1.5 | 1.5 | 5.76 | |
| 10.5 | 9.4 | 1.8 | 5.85 | |
| 12.6 | 1.3 | 2.0 | 6.29 | |
| 16.3 | 1.4 | 2.3 | 7.07 | |
| 17.5 | 0 | 2.6 | 6.74 | |
| 24.6 | 0 | 3.5 | 7.02 | |
| 17.5 | 4.6 | 2.6 | 6.74 | |
| 16.3 | 3.0 | 2.3 | 7.07 | |
| 8.64 | 0 | 1.5 | 5.78 | |
| 12.6 | 1.6 | 2.0 | 6.29 | |
| 5.54 | 0 | 1.2 | 4.65 | |
| 5.81 | 0 | 1.2 | 4.84 | |
| 7.58 | 0 | 1.5 | 5.04 | |
| 7.58 | 0 | 1.5 | 5.04 | |
| 8.05 | 0 | 1.5 | 5.37 | |
| 7.0 | 0 | 1.2 | 5.82 | |
| 18 | 0 | 2.8 | 6.42 | |
| 25.3 | 0.16 | 3.8 | 6.65 | |
| 30.5 | 0 | 5.1 | 5.96 | |
| 13.1 | 9.6 | 1.8 | 7.28 | |
| 12.2 | 0 | 2.0 | 6.12 | |
| 15.5 | 0.16 | 2.3 | 6.73 | |
| 18.9 | 5.5 | 2.5 | 7.54 | |
| 17.5 | 0.3 | 2.5 | 7.01 | |
| 25.3 | 0.12 | 3.8 | 6.65 | |
| 30.5 | 0 | 5.1 | 5.96 | |
| 14.5 | 0 | 3.9 | 4.98 | |
| 7.3 | 0 | 1.8 | 3.70 | |
| 13.0 | 0 | 2.2 | 5.90 | |
| 13.1 | 1.94 | 1.8 | 7.28 | |
| 15.5 | 0 | 2.3 | 6.73 | |

## TABLE D-2

## DATA FROM SAN LUIS VALLEY CANALS REPORTED BY LANE AND CARLSON

| | Observed (1952) | | | | | | Calculated | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Test Section | Discharge Q c.f.s. | Top Width Ft. | Mean Depth d Ft. | Slope of Energy Grade line x $10^3$ | Mean Velocity V Ft./Sec. | $m_wD$ Ft. | $\frac{V^2}{d}$ | $\frac{V^2}{(s-1)gd}$ | $\frac{d}{m_wD}$ | Remarks |
| 1 | 1500 | 73 | 4.87 | 2.80 | 5.88 | 0.27 | 7.1 | 0.141 | 18.0 | S=2.56 (ref. 39) |
| 2 | 668 | 55 | 2.81 | 3.76 | 5.83 | 0.25 | 12.1 | 0.24 | 11.2 | Test section - |
| 4 | 768 | 48 | 3.11 | 3.59 | 6.53 | 0.25 | 13.7 | 0.27 | 12.4 | straight and regular |
| 5 | 448.2 | 40 | 2.50 | 3.68 | 5.82 | 0.18 | 13.6 | 0.27 | 14.0 | Length = 600 - 2200 Ft. |
| 6 | 159 | 21.7 | 1.88 | 2.95 | 4.59 | 0.14 | 11.2 | 0.223 | 13.4 | $V_{mean} = Q/A$ |
| 7 | 95.6 | 15.9 | 1.73 | 2.90 | 4.36 | 0.14 | 11.0 | 0.22 | 12.3 | Cross sectional |
| 8 | 46.0 | 19.2 | 0.95 | 3.16 | 3.00 | 0.13 | 9.4 | 0.19 | 7.4 | areas, hydraulic |
| 10 | 16.6 | 11.1 | 0.60 | 9.65 | 2.90 | 0.21 | 14.0 | 0.28 | 2.9 | radii and depths |
| 11 | 203.0 | 32.3 | 1.88 | 2.35 | 3.88 | 0.16 | 8.0 | 0.16 | 11.8 | of sections were |
| 12 | 128.0 | 21.9 | 1.77 | 2.43 | 4.00 | 0.11 | 9.05 | 0.18 | 16.1 | averaged to obtain the mean values in the computation (Ref. 40) |
| 14 | 110.0 | 21.4 | 2.0 | 1.36 | 3.29 | 0.07 | 5.4 | 0.107 | 29.0 | |
| 15 | 477.0 | 39.4 | 3.05 | 1.99 | 4.84 | 0.164 | 7.7 | 0.153 | 18.6 | |
| 17 | 531.0 | 41.0 | 2.60 | 2.74 | 5.51 | 0.13 | 11.7 | 0.233 | 20.0 | |
| 18 | 235.0 | 25.0 | 2.94 | 0.80 | 3.80 | 0.07 | 4.94 | 0.098 | 42.0 | |